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Resistive evolution of the magnetized Kelvin-Helmholtz instability

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Summary. — It is found from the resistive MHD simulation that the most effective momentum transport due to Kelvin-Helmholtz instability is obtained in the small range of magnetic-field intensity when the highly sheared field lines undergo magnetic reconnection in the late stage of the evolution.

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1. – Introduction

It has been suggested that the Kelvin-Helmholtz (KH) instability at the magnetopause boundary can yield a viscous interaction which transports momentum and energy through the boundary [1-3]. A residual convection potential drop ~ 35 kV over the polar cap, which is not controlled by the orientation of the interplanetary magnetic field, is accounted for by such a viscous interaction [4]. The magnetohydrodynamic (MHD) simulation studies indeed demonstrated that the anomalous viscosity generated by the KH instability is sufficient for accounting for the observed tailward momentum flux in the low-latitude boundary layer [5-7]. However, these simulation studies were performed only up to the stage in which KH instability is in its full development and the magnetic field is highly sheared. Study on the long-term evolution of the KH instability and the role of reconnection of these highly sheared magnetic-field lines in the late stage evolution has only recently started [8]. It was shown that magnetic reconnection plays an important role in reorganizing the highly structured field lines when the field intensity is not too strong and magnetic-field lines become flattened in the final stage. In this paper, by adopting the similar resistive MHD simulation study of the KH instability, we demonstrate that momentum transport and energy conversion are most effective in the small range of the magnetic-field intensity when the long-term evolution of the instability is considered.

2. – Results

The initial velocity profile for the present simulation study is given by

$$V_x = 0.5 \operatorname{tgh}((y-50)/L) ,$$

in which the shear scale length L is 6. We have considered three cases for the uniform initial magnetic field: $B_x = 1/3$, $B_x = 1$, and $B_x = 1/6$. Alfvenic and sonic Mach numbers for $B_x = 1/3$ are $M_A = 10$ and $M_S = 1$, respectively. All these configurations are unstable to the KH instability.

Figure 1 shows the time evolution of magnetic-field lines when the initial B_x is equal to $1/3$. It is seen that the field lines wrapped around the vortex at $t = 700$ when the KH instability is well developed in fig. 1*a*) become reconnected (fig. 1*b*)) and flattened finally (fig. 1*c*)). The final field line configuration, although it resembles the initial magnetic field, is not uniform. The magnetic field is small in the central region, while it is somewhat enhanced just outside this field depletion region. Plasma flow vectors are mostly parallel (or anti-parallel) to the magnetic field lines. The new velocity shear in the final configuration is very broad with its shear length scale $L \sim 35$, which makes the new configuration stable against the KH instability.

When the initial magnetic field intensity is increased ($B_x = 1$ in the present study), the field line development is markedly different although it shows the signatures of the

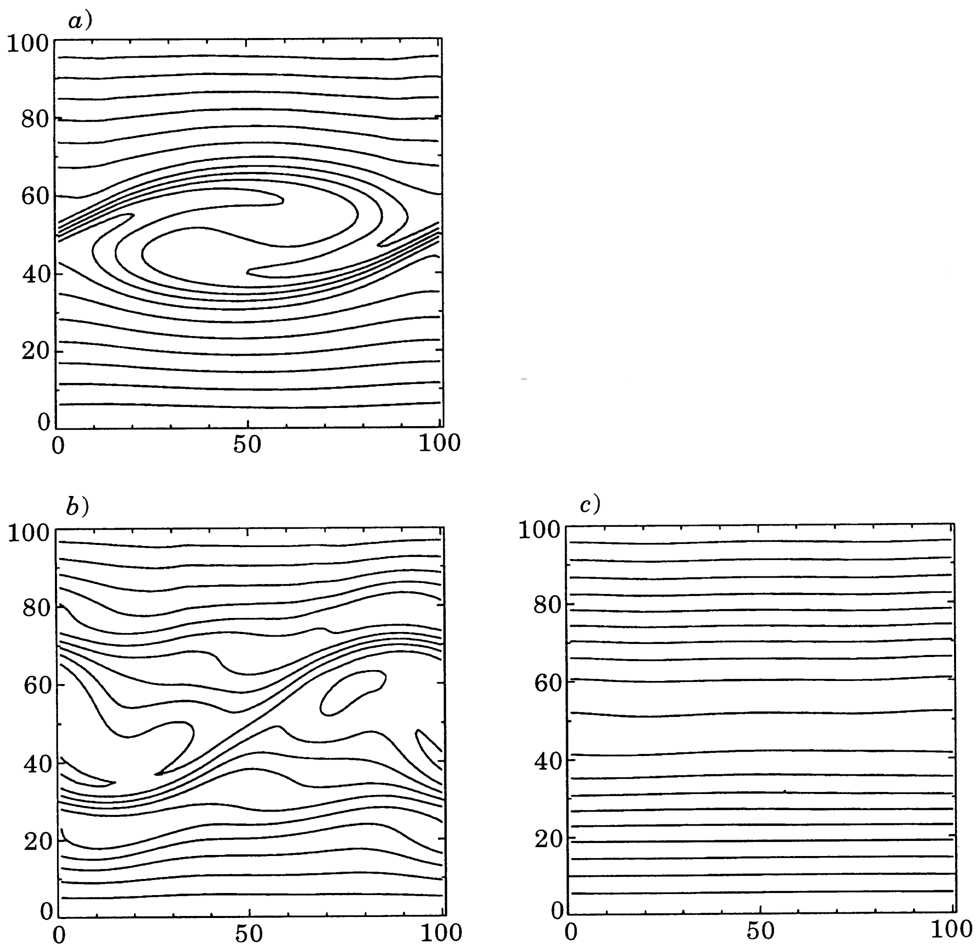

Fig. 1. – Time evolution of the magnetic-field lines for $B_x = 1/3$; *a*) at $T = 700$, *b*) at $T = 1400$, and *c*) at $T = 4200$.

KH instability in the initial stage. The enhanced magnetic field due to the dynamo action of the KH instability reacts back to the plasma flow and the field line straightens without involving magnetic reconnection. When the magnetic field is very weak, the stabilizing effect of the magnetic field is not significant and the KH instability becomes mostly hydrodynamic. Although a lot of magnetic reconnections operate in this case, the hydrodynamic nature of the instability is dominant and magnetic reconnection plays a minimal role in the dynamic evolution.

Sharp velocity shear is the free energy source for the KH instability and it becomes broad as the instability grows. The final velocity profiles for the three cases considered in the present study are shown in fig. 2. In fig. 2*a*) for $B_x = 1/3$, the velocity profile at $t = 700$, at which the KH instability is well developed but magnetic reconnection is not

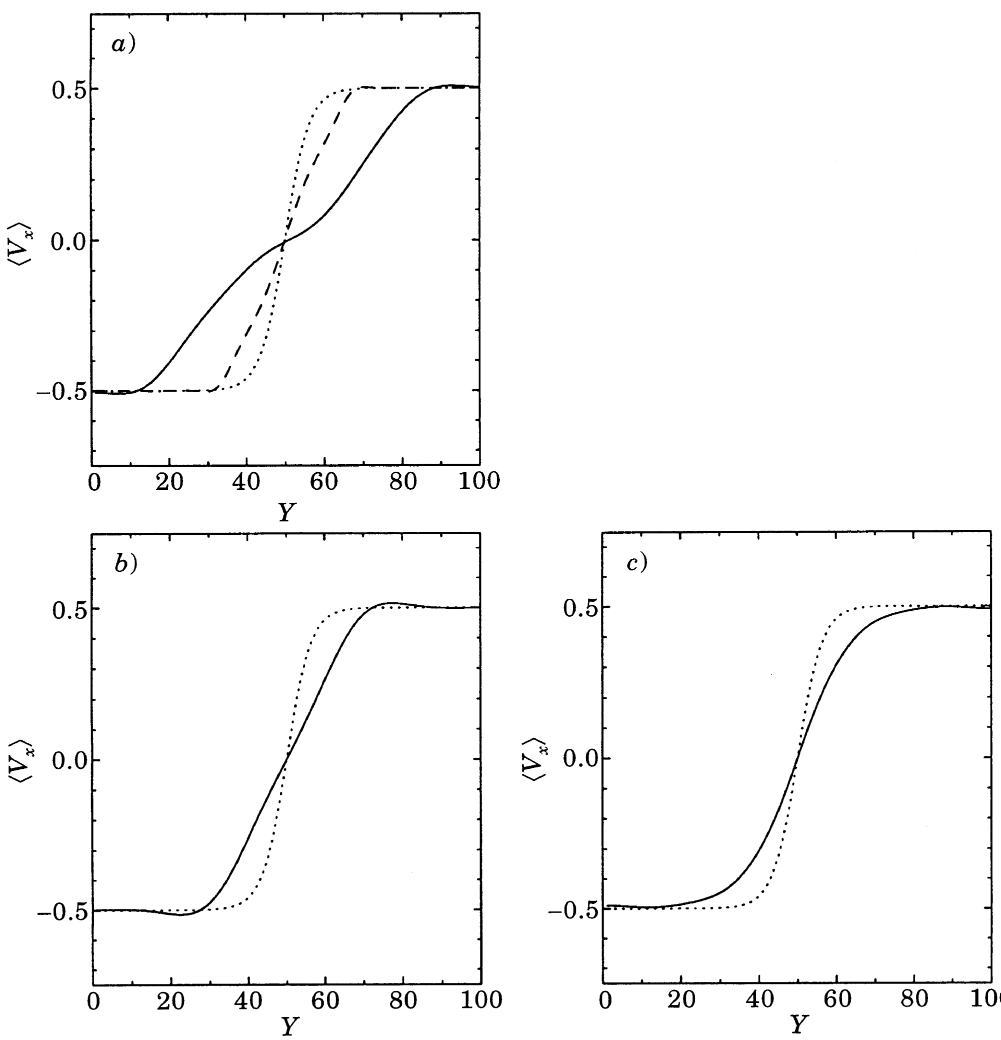

Fig. 2. – Change in the velocity profile: *a*) for $B_x = 1/3$, *b*) for $B_x = 1$, and *c*) for $B_x = 1/6$. The dotted lines are for the initial velocity profiles and the solid lines are the velocity profiles at $t = 4200$. The dashed line in *a*) represents the velocity profile at $t = 700$.

yet in operation, is also shown. The same figure shows clearly that magnetic reconnection plays an important role in the second stage of the KH instability. While the final velocity shear boundary becomes very broad in the case $B_x = 1/3$, other two cases shown in fig. 2*b*) and *c*) have rather narrow velocity shear profiles. The velocity profile in fig. 2*c*) for $B_x = 1/6$ shows some changes far out of the shear region, but the amount of the change is very small compared to that of the case $B_x = 1/3$.

Figure 3 depicts the time evolution of the Reynolds stress (hydrodynamic stress) and the Maxwell stress (electromagnetic stress) averaged over one wavelength in the x-direction at the velocity shear boundary $y = 50$. These stresses represent the amount of the momentum transport across the shear boundary. It is seen in fig. 3*a*) that the Reynolds stress changes its sign as the KH instability develops, while the Maxwell stress increases monotonically and becomes dominant over the Reynolds stress at $t = 700$.

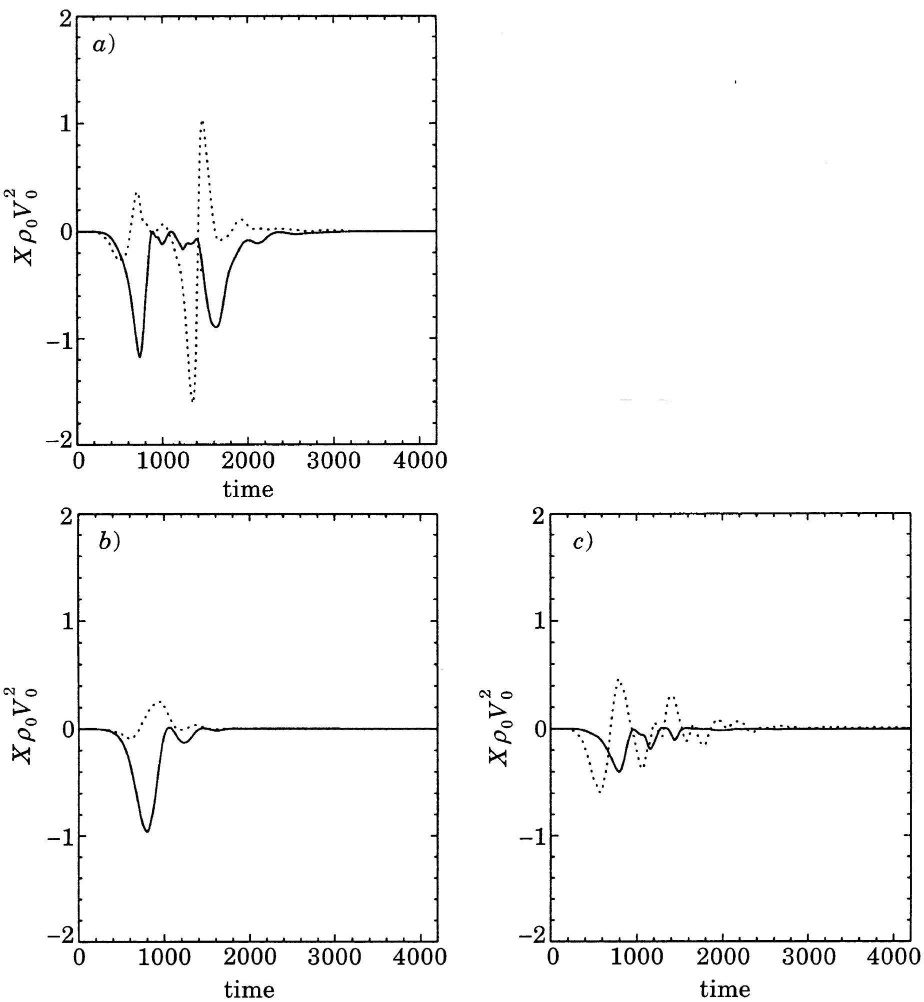

Fig. 3. – The time evolution of the stresses across the velocity shear boundary: *a*) for $B_x = 1/3$, *b*) for $B_x = 1$, and *c*) for $B_x = 1/6$. The dotted lines are for the hydrodynamic (Reynolds) stress and the solid lines are for the electromagnetic (Maxwell) stress.

However, the Maxwell stress soon decreases as magnetic reconnection develops. In the subsequent evolution very large Reynolds stress develops as the second-stage KH instability grows, but it oscillates and the Maxwell stress takes over again as a result of the dynamo action. Finally, the stresses become negligible as the field line flattens and the plasma flows are aligned with the magnetic field. Oscillation of the Reynolds stress and the peaks of the Maxwell stress are also seen in fig. 3*b*), in which $B_x = 1$, and in fig. 3*c*), in which $B_x = 1/6$. Although the peaks are prominent in all three cases, the most effective momentum transport is seen in the case $B_x = 1/3$.

Figure 4 shows the energy conversion among the bulk plasma flow energy, thermal energy, and the magnetic energy for the three cases discussed here. As can be seen in the figures, most of the plasma flow energy goes into the form of plasma thermal

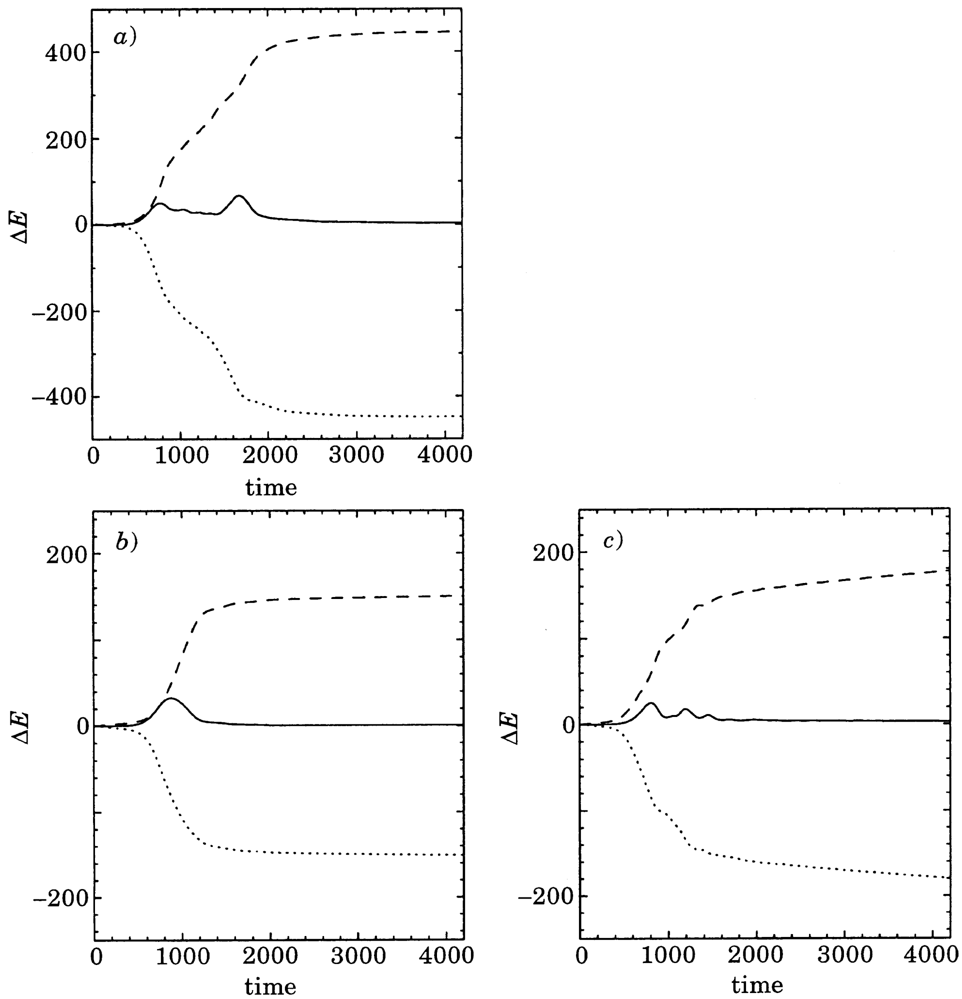

Fig. 4. – The change in the energy integrated over the whole simulation domain: *a*) for $B_x = 1/3$, *b*) for $B_x = 1$, and *c*) for $B_x = 1/6$. The dotted lines are for the bulk plasma motion energy, the dashed lines are for the thermal energy, and the solid lines are for the magnetic energy. Note the scale changes in *b*) and *c*).

energy. In the case of $B_x = 1/3$ shown in fig. 4*a*), the magnetic energy steadily increases due to the dynamo action until $t = 800$ and it decreases subsequently as the magnetic reconnection operates. The magnetic energy peaks again just after $t = 1600$ in the second stage of the KH instability and it decays therafter. The system becomes more or less stable after $t = 2000$ with no more energy conversion. For the stronger magnetic-field case ($B_x = 1$) shown in fig. 4*b*) the system reaches the steady state in the sense of energy conversion as early as $t = 1200$. The magnetic energy shows only one peak, and this peak is smaller than those of the case $B_x = 1/3$. The amount of the energy conversion from the bulk flow energy into the form of thermal energy is less than half of that for $B_x = 1/3$. For the weak magnetic-field case ($B_x = 1/6$) we see at least three peaks in the magnetic energy during the evolution, but they are smaller than those of the case $B_x = 1/3$. The amount of the energy conversion from the bulk flow energy into the form of thermal energy is again less than half of that for $B_x = 1/3$, although a very slow energy conversion is still seen at the final stage $t = 4200$.

3. – Summary

Resistive MHD simulation study is performed to investigate the momentum transport through the velocity shear boundary when the highly sheared magnetic-field lines induced by the KH instability undergo magnetic reconnection.

For the particular choice of $B_x = 1/3$ in the present study, the field lines wrapped around the KH vortex become reconnected and flattened finally. The dynamo action of the KH instability and magnetic reconnection repeated intermittently, so that the final configuration with broad velocity shear becomes stable against the KH instability. For magnetic fields stronger than this ($B_x = 1$ in the present study) KH instability does not develop much. For smaller magnetic fields ($B_x = 1/6$ in the present study) dynamo action of the KH instability does not generate an energetically significant magnetic field compared to the plasma flow energy and the field line reconnection plays a minimal role in the dynamic evolution.

It is shown that the case of $B_x = 1/3$ is consistently most effective in the broadening of the velocity shear, momentum transport measured by means of the stresses across the shear boundary, and in the energy conversion. When the magnetic field is too strong, it stabilizes the vortex growing early on; while, for a weak magnetic field, the instability is mainly hydrodynamic and magnetic reconnection has a negligible effect on the energetics of the dynamical evolution. In conclusion, it seems that there is a limited range of magnetic-field strength in which the KH instability is most effective in the long-term evolution when it is combined with magnetic reconnection.

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