# Magnetic Effects on the Coalescence of Kelvin-Helmholtz Vortices

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We simulate the coalescence process of MHD-scale Kelvin-Helmholtz vortices with the electron inertial effects taken into account. Reconnection of highly stretched magnetic field lines within a rolled-up vortex destroys the vortex itself and the coalescence process, which is well known in ordinary fluid dynamics, is seen to be inhibited. When the magnetic field is initially antiparallel across the shear layer, on the other hand, multiple vortices are seen to coalesce continuously because another type of magnetic reconnection prevents the vortex decay. This type of reconnection at the hyperbolic point also changes the field line connectivity and thus leads to large-scale plasma mixing across the shear layer.

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The Kelvin-Helmholtz (KH) vortex has been considered to be one of the most important agents in space plasma systems involving a sheared flow, such as at a planet's magnetopause or in the solar wind [1–4]. Large-scale (MHD-scale) development of KH vortices is expected to lead to large-scale plasma mixing across a shear layer, as observed in Earth's magnetosphere [5–7]. In understanding the large-scale development and associated large-scale plasma mixing, coalescence of vortices is the key issue. When the system contains multiple KH vortices ($L > \lambda_{\mathrm{KH}}$, L: system size, $\lambda_{\mathrm{KH}}$: KH wavelength), it is well known in the ordinary hydrodynamics that the vortices coalesce into a larger vortex [8,9].

A variation of this picture emerges in a magnetohydrodynamic (MHD) system. In MHD, a density jump across a shear layer can be sustained by a corresponding change in the magnetic field intensity as seen at a planetary magnetopause. Such a large density jump has been shown to stop the coalescence process since rolled-up vortices are destroyed by the secondary Rayleigh-Taylor instability growing within them [10].

While the above study considered only the magnetic component perpendicular to the flow, it has been shown that the dynamics of KH vortices is affected significantly by the in-plane magnetic component [11,12]. Here, the in-plane magnetic field means the magnetic field along $k$ vector of KH instability (KHI). The in-plane magnetic field tends to suppress the linear growth of KHI [12] as well as the growth of a fully rolled-up vortex [13]. Moreover, the in-plane field lines are deformed highly by the vortex flow and then can be reconnected [14–17]. Indeed, evidence of such magnetic reconnection process has been recently reported at the Earth's magnetopause [18]. Nakamura *et al.* [17] has summarized the effects of two types of magnetic reconnection within a KH vortex. (1) Type I occurs when the in-plane field is initially antiparallel across the shear layer (antiparallel case). Reconnection is induced at the hyperbolic point. Type I is possible for both strong and weak shear flows. (2) Type II is driven when the velocity shear is strong enough (or, in-plane magnetic field is weak enough) to produce highly rolled-up KH vortices. In a type II case, the field lines that have been amplified and stretched by the strong rolling-up flow are reconnected.

In the above study, only one vortex is allowed to grow in the simulation box. The purpose of the present study is to see how the in-plane magnetic component affects vortex coalescence via the two types of reconnection described above. The simulations are done using two-dimensional (on the $X$-$Y$ plane including the velocity shear flow) two-fluid (ion and electron fluids) equations including finite electron inertia (mass). [See Nakamura *et al.* (2004) [3] for the exact form of the equations.] In a two-fluid system, when the system length is comparable to the electron inertial length ($L < \lambda_e$), the electron inertial term can break the frozen-in condition, and magnetic reconnection occurs spontaneously without an addition of *ad hoc* resistivity [17,19]. Thus, the two-fluid simulation would be a reasonable choice for studying MHD-scale phenomena involving dynamically triggered magnetic reconnection, such as reconnection induced in a vortex flow [17].

In this study, we consider fundamental cases whose initial conditions have only in-plane magnetic field and uniform density. Two distinctive situations are considered regarding the initial magnetic configuration. (1) The magnetic field is uniform across the velocity shear layer (the parallel case). (2) The magnetic field is antiparallel across the shear layer, $B_{X0} = \tanh(Y/D)$ (the antiparallel case). The initial shear flow of ion and electron is given by $V_{iX0} = -V_0 \tanh(Y/D)/2$. Here $V_0$ is the initial velocity jump and D is the initial half thickness of the shear layer. Using the initial density and the magnitude of the initial magnetic field, velocity, time, and length are normalized by the ion Alfvén velocity, inverse of the ion gyrofrequency, and the ion inertial length, respectively. The system is periodic in the flow ($X$) direction with its size equal to 8 times the wavelength of the fastest KH mode $Lx = 8\lambda_{\mathrm{KH}} = 120$ D

 

[12]. Conducting walls are located at $Y = \pm 80$ D. The ion-to-electron mass ratio $M = 25$ and $D = 1.0$ unless otherwise noted. Plasma beta based on in-plane magnetic component is $1.2V_0^2$. The spatial and temporal scales are mostly described by the hydrodynamic unit D and $D/V_0$, respectively, because KHI is hydrodynamics in nature. To initiate KHI, we add a small flow perturbation $\delta V_{iY} = \delta V_0 \exp[-(Y/D)^2]\sin(2\pi X/\lambda_{KH})$ as well as a small amplitude ($10^{-3}$) random perturbation in the magnetic field. Here, $\delta V_0$ is the amplitude of the perturbation, which is chosen as 0.02 in the normalized unit.

Three cases will be shown: Parallel and strong shear, antiparallel and strong shear, and antiparallel and weak shear. Here, the strong shear corresponds to $V_0(= M_A) > 5$, where $M_A$ is the Alfvén Mach number of the shear flow based on the in-plane field. Only when $M_A > 5$ the KHI produces a highly rolled-up vortex [13].

Figure 1 shows the pressure pattern $\Delta P$ ($= P - P_0$) for the $M_A = 10$ and parallel case. First, eight KH vortices highly rolled-up ($T = 75$). The width of each vortex is 4 times the initial thickness of the shear layer. Low-pressure peaks are located around the vortex centers as in a well-known hydrodynamic case. Unlike a hydrodynamic case, however, magnetic reconnection (type II reconnection) is triggered within each rolled-up vortex to relax the concentrated magnetic field lines ($T = 100$). While the initial magnetic field is rather weak, the field subject to type II reconnection is amplified and the flow disturbance produced by the reconnection is as viable as to lead to the vortex decay ($T = 200$). Then further coalescence of KH vortices cannot be observed. Instead one can see that larger vortices emerge ($T = 400$). The wavelength of these vortices is about a factor of 4 larger than the initial one. Figure 2 shows the $Y$ profile of the $Vx$ component averaged over the $X$ direction at $T = 0$ and 200. After the destruction of the vortices, the shear layer increases its width by a factor of 4. These findings lead to the scenario as follows: (1) Type II reconnection destroys the first generation vortices. (2) A broadened velocity shear layer whose thickness is comparable to the thickness of the first generation vortices forms. (3) Secondary KHI grows in the thickened shear layer. (4) The second generation vortices having a wavelength that is 4 times larger emerge.

Figure 3 shows the result for the $M_A = 10$ and antiparallel case. Eight vortices, which roll-up with type I reconnection occurring concurrently, coalesce into four vortices ($T = 250$). Subsequently, four vortices continuously coalesce into two vortices ($T = 375$), and eventually one large vortex is formed ($T = 600$). That is, unlike the previous case, coalescence proceeds continuously. Type I reconnection connects the magnetic field lines across the shear layer and prevents the type II reconnection to have significant effects. The latter is because type I sets in earlier and then inhibits the concentration of magnetic field lines inside rolled-up vortices.

A simple picture for these high $M_A$ (weak magnetic field) cases is that the magnetic field would not play any major role and the results are essentially the same with an ordinary fluid case. Our results show that, via two types of magnetic reconnection within KH vortices, the in-plane

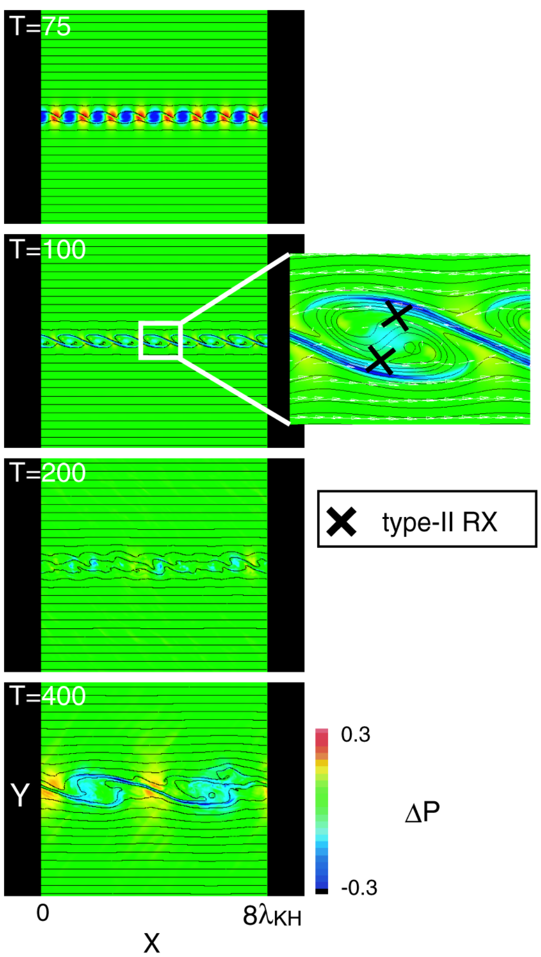


FIG. 1 (color online). $\Delta P$ ($= P - P0$) contours and magnetic field lines for the $M_A = 10$ (weak magnetic field) parallel case.

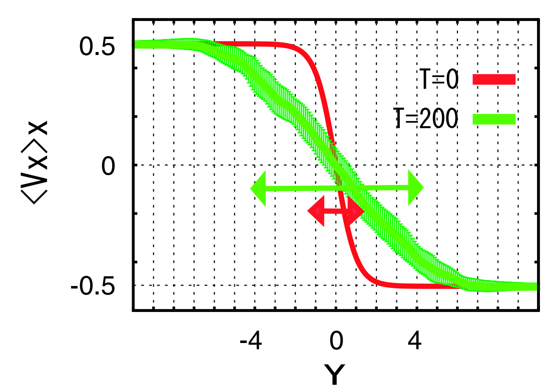


FIG. 2 (color online). Profiles of $Vx$ averaged in the $X$ direction at $T = 0$ and $T = 200$ for the $M_A = 10$ parallel case. The envelope for the $T = 200$ profile shows the standard deviation, whose small amplitude indicates that vortices are lost.

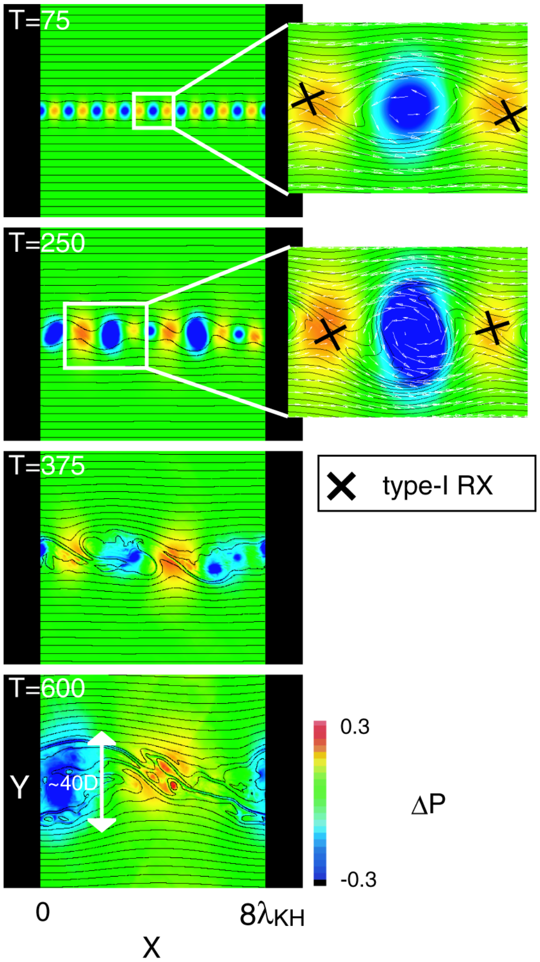


FIG. 3 (color online). $\Delta P$ contours and magnetic field lines for the $M_A = 10$ antiparallel case.

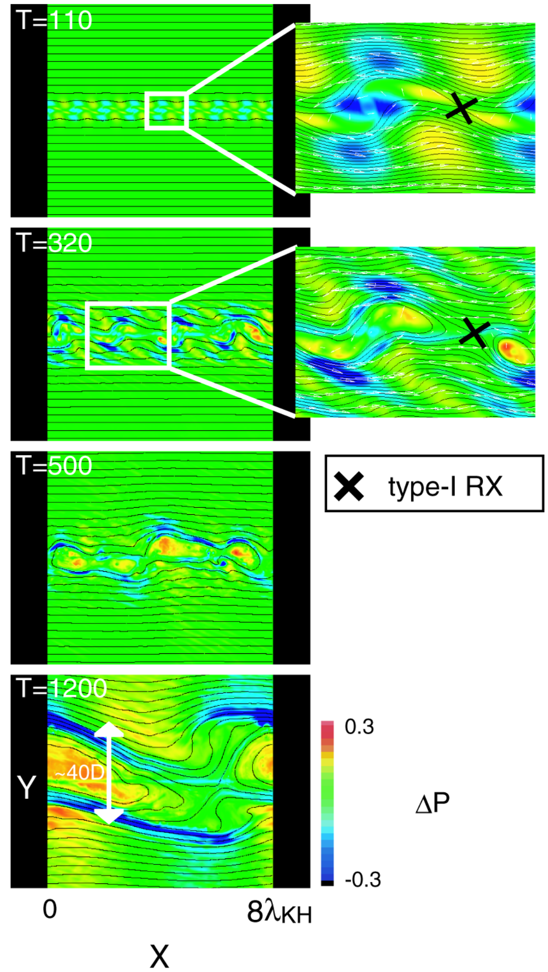


FIG. 4 (color online). $\Delta P$ contours and magnetic field lines for the $M_A = 3$ (strong magnetic field) antiparallel case.

magnetic field, even though weak in the initial phase, does control the large-scale development of the vortices.

Next we investigate the low $M_A$ ($2 < M_A < 5$) case. Here the KHI itself is too weak to produce a highly rolled-up vortex. (When $M_A < 2$, the KHI is stable [12].) An interesting feature appears in the antiparallel and weak KHI case, in which type I reconnection assists the KH vortex to highly roll-up [17]. Figure 4 shows the result for the $M_A = 3$ and antiparallel case. With the growth of KHI, the current sheet is compressed at the hyperbolic points where the flow converges from above and below, and then type I reconnection is induced ($T = 110$). Subsequently, 8 magnetic islands (8 vortices) produced by type I reconnection begin to coalesce, and eventually into one large magnetic island (vortex) ($T = 1200$). In this weak and antiparallel case, in contrast to the strong KHI cases, pressure at the center of the vortices tends to be peaked positively. That is, the pressure pattern behaves as in a magnetic island situation where the center of the island corresponds to magnetic null and higher plasma pressure at the center is needed for the force balance reason. We have confirmed the same sequence to be observed in the $Lx = 16\lambda_{KH}$ case, where 16 rolled-up vortices continuously coalesce into one large vortex.

From the plasma transport point of view, it has been known that the antiparallel case is important because plasma mixing across the shear layer can develop inside the vortex on the field lines subject to type I reconnection [17]. The results from the two antiparallel cases of this study indicate that the large-scale plasma mixing proceeds with the progression of vortex (island) coalescence. Our results with a higher mass ratio (up to $M = 400$) and a thicker shear layer (up to $D = 4$) also confirm that the essential results are unaffected by $M$ and $D$. These results indicate the scalability of the conclusion within the fluid and two-dimensional approximations. This result may describe the underlying physics leading to a formation of large magnetic island at the Earth's magnetopause [20]. Moreover, the results are consistent with observations at the Earth's low-latitude boundary layer where the mixed plasma of magnetosheath and magnetosphere origins is often detected accompanied by undulated signature of the boundary with the plasma mixing region becoming thicker with distance down the tail [6,7].

Under a northward interplanetary magnetic field condition, the plasma mixing at the boundary has been known to develop most [6]. An analysis of a realistic Earth's magnetopause situation under this condition shows that the most unstable KH mode has the in-plane magnetic field changing sign across the magnetopause [17]. Then, as discussed in the previous paragraph, growth and coalescence of KH vortices can directly lead to large-scale plasma mixing. While density gradient and out-of-the-plane magnetic field are present in a realistic situation [17], we have confirmed that the essential results of the coalescence process are unchanged by these effects. At the same time, the expansion in vortex size causes the Earth's magnetopause boundary to be undulated by larger amplitude. When three-dimensionality is taken into account, the large amplitude surface waves may launch intense kinetic Alfvén waves that also facilitate plasma mixing across the boundary [21]. While the parent KHI is MHD in nature, it is the coupling to non-MHD dynamics that makes the instability put on important roles in the plasma transport process.

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