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Interaction of magnetic reconnection and Kelvin-Helmholtz modes for large magnetic shear: 2. Reconnection trigger

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Abstract A typical property of magnetopause reconnection is a significant perpendicular shear flow due to the fast streaming magnetosheath plasma. Therefore, the magnetopause represents a large magnetic and flow shear boundary during periods of southward interplanetary magnetic field, which can be unstable to Kelvin-Helmholtz (KH) modes and to magnetic reconnection. A series of local three-dimensional MHD and Hall MHD simulations is carried out to investigate the interaction of reconnection and nonlinear KH waves considering magnetic reconnection as the primary process. It is demonstrated that the onset reconnection causes a thinning of the shear flow layer, thereby generating small wavelength KH modes. In turn, the growing KH modes modify the current layer width, which modulate the diffusion regions, increase the local reconnection rates, and generate field-aligned currents. The simulation results imply a limitation of total amount of open flux likely caused by nonlinear saturation of KH growth and the associated diffusion. It is also demonstrated that the reconnection rate maximizes for conditions that allow a strong nonlinear evolution of KH waves, i.e., fast shear flow and limited guide magnetic field. The presence of Hall physics increases the reconnection rate in the early stage; however, the maximum reconnection rate and the total amount of open flux at saturation are the same as in the MHD case.

1. Introduction

A critical problem of magnetospheric physics is the plasma transport from the solar wind into the Earth's magnetosphere. Magnetic reconnection and viscous interactions are suggested as the two basic mechanisms for transport at the magnetospheric boundary [Dungey, 1961; Axford, 1964]. It is well known that dayside reconnection operates for southward interplanetary magnetic field (IMF) conditions. Recently, nonlinear Kelvin-Helmholtz (KH) waves were observed during southward IMF [Hwang et al., 2011]. Their analysis revealed a mixture of KH waves at different amplitudes with inconsistent variations in scale size and magnetic perturbations compared to an expected evolution of KH structures. Further analysis indicated that the observed KH waves appeared to be irregular and intermittent for southward IMF. Fast magnetic reconnection [Petschek, 1964] generally requires large antiparallel magnetic field components, which are satisfied at the equatorial magnetospheric boundary for southward IMF conditions. A central property of magnetic reconnection is the breakdown of the so-called “frozen-in” condition by localized dissipation in the diffusion region, which changes the topology of the magnetic field lines and allows solar wind plasma access to the magnetosphere. Theoretical analysis and numerical simulations show that a typical fast reconnection rate is about 0.1VₐB₀ [Petschek, 1964; Bim et al., 2001], where Vₐ is the inflow Alfvén speed corresponding to the inflow magnetic field B₀. For northward IMF conditions, magnetic reconnection is expected to occur close to the geomagnetic cusp regions [Adamson et al., 2012].

Close to the Earth’s magnetopause and away from the subsolar point, a large shear flow always exists due to the shocked solar wind streaming past the Earth’s magnetosphere. The shear flow renders this boundary potentially unstable to the Kelvin-Helmholtz (KH) instability, which is clearly observed in global MHD simulations for both northward [Guo et al., 2010; Li et al., 2012, 2013] and southward [Hwang et al., 2011] IMF conditions. Observational evidences for nonlinear KH waves during the northward IMF conditions have been reported by different authors [Fairfield et al., 2000; Otto and Fairfield, 2000; Hasegawa et al., 2004]. Large-scale nonlinear KH waves can generate a significant exchange of momentum across a physical boundary, thereby introducing a viscous interaction in the plasma participating in this interaction. This process, as well as an efficient transport of energy across the plasma boundary, has been demonstrated by a number of two-dimensional MHD simulations [Miura, 1982, 1984, 1987, 1992, 1996]. However, as an ideal instability, the KH instability does not violate the frozen-in condition in ideal MHD, such that no plasma transport is
two-dimensional numerical simulations of reconnection and KH waves [La Belle-Hamer et al., 1995; Chen, 1997]. However, the assumed two-dimensional configuration in La Belle-Hamer et al. [1995] excludes the KH modes because their k vector is in the invariant direction. This is different in three dimensions, where magnetic reconnection and KH waves can operate simultaneously. In the linear stage, the growth rates of these two modes and the respective initial perturbations determine the dominant dynamic process (Chen, 1997). In the nonlinear stage, the interaction of these processes has not been fully understood. This question can be approached from two different angels, namely by assuming conditions where (1) KH modes represent the initial or primary process and (2) magnetic reconnection is the primary process. Our companion paper (hereafter referred to KH1) examines the case where the KH mode is the primary process. The present work examines the second condition.

The numerical methods are similar to KH1 and are briefly described in section 2. In section 3, the overall dynamics processes are presented and are followed by the investigation of the dependency upon the shear flow and guide field. The presence of Hall physics has also been discussed in this section. Section 4 is the summary and discussion.

2. Numerical Methods

In this study we use the leap-frog method to solve the full set of the resistive Hall MHD equations, which has been discussed by Otto [1990, 2001]. In the computations all quantities are normalized to the typical values, as outlined in KH1 and the normalization uses B0 = 20 nT, for the magnetic field, n0 = 10 cm⁻³, for number density, and L0 = 640 km, for the length scale.

A series of selected simulation results are presented to study the interaction between magnetic reconnection and KH modes. For comparison with KH1, we use the same simulation domain, that is, |x| ≤ Lx = 30, |y| ≤ Ly = 20, and |z| ≤ Lz = 40, and is resolved by using 103 x 203 x 103 grid points with a nonuniform grid along the x and z directions. Here x is the normal direction from the magnetosphere to the magnetosheath, y is along the boundary and along the shear flow, and z is along the antiparallel magnetic field (as illustrated in Figure 1). The best resolution is set to 0.1 and 0.2 in the x and z directions in the vicinity of the current layer where reconnection is triggered. The initial equilibrium is a one-dimensional modified Harris sheet, given by B = B₀̂e₀ - B₀ tanh(x)̂e_z, V = -V₀ tanh(x)̂e_z, p = p₀ + 1 - B₀², and ρ = ρ₀ + δρ tanh(x), where B₀ = 1, p₀ = 0.25, ρ₀ = 1, δρ = 0.1, B₀ is the guide field, and V₀ is the initial shear flow magnitude. In two dimensions, super fast mode shear flow can stabilize the KH mode, because the obstacle information cannot propagate in the downstream direction [Miura and Pritchett, 1982]. Therefore, the flow velocity is represented by the fast mode Mach number, Mf = V_f/V, where V_f = (B₀² + γrho₀²)/ρ₀ = 1.1 is the average fast mode speed. The reference case uses B_p = 0 and Mf = 0.5. Figure 1 shows a sketch of the three-dimensional system, where magnetic shear, shear flow, and the source region for reconnection are indicated. In order to select magnetic reconnection as the primary process, reconnection is initiated in a source region by a
magnetic perturbation which is chosen as \( \delta \mathbf{B} = n f_j(y), \) where \( A(x, z) = \delta B \cosh^{-2}(x) \cosh^{-2}(z/2) \), and \( \delta B = 0.5 \). The function \( f_j \) is given by

\[
f_j(y) = C \left[ \tanh \left( \frac{y + y_0}{a} \right) - \tanh \left( \frac{y - y_0}{a} \right) \right],
\]

with \( C = 0.5 \tanh^{-1}(y_0/d) \), \( y_0 = 10 \), and \( d = 2 \) and is chosen to localize the perturbation in the region where \( y < |10| \). The relatively large magnetic perturbation serves to accelerate the evolution of reconnection as the primary instability in this study.

The simulations use periodic boundary conditions along the \( y \) direction, and closed boundary \( (B_y = V_y = 0) \) conditions are applied in the \( x \) direction. The simulation box is chosen sufficiently wide in \( x \) that boundary effects are negligible. As in KH1, an artificial friction term, \( -\nu(z) [\rho \mathbf{V} - (0) \mathbf{V}(0)] \), is added in the momentum equation to mimic the fact that the magnetosheath magnetic field lines are moving with the solar wind and that the magnetospheric magnetic field is tied to the Earth's ionosphere.

The resistivity models for the present results are the same as in KH1 and based on the assumption that microturbulence is switched on once a critical drift speed for the current carriers is surpassed. Specifically, three different models are used, which are given by the following:

\[
\begin{align*}
\text{Model 1:} & \quad \eta_1 = \eta_0 \sqrt{P - j^2 \hat{H} (j - j_0)} + \eta_b, \\
\text{Model 2:} & \quad \eta_2 = \eta_0 \sqrt{1 - j^2 \hat{H} (j - j_0)} + \eta_b, \\
\text{Model 3:} & \quad \eta_3 = \eta_0 (j - j_0) \hat{H} (j - j_0) + \eta_b,
\end{align*}
\]

where \( \eta_0 = 0.05 \), \( H(x) \) represents a step function, \( j_0 = \rho \nu_c = \sqrt{2\eta p} \) is the critical current density, and \( \eta_b = 0.001 \) is a background resistivity. However, we will demonstrate that the specific choice has only a minor influence on the evolution in the considered cases. Therefore, unless stated otherwise, we always use Model 1.

## 3. Simulation Results

### 3.1. Overall Dynamics

Figure 2 presents the open magnetic flux and the normalized reconnection rate by tracing the magnetic field line from the top boundary for different resistivity models. The identification of open and closed field lines has been described in KH1. All other parameters are the same (i.e., \( B_\perp = 0 \) and \( M_f = 0.5 \)) and the result for the run with resistivity model 1 is used as a reference case. The results demonstrate that reconnection starts to operate at about \( t = 15 \). The open flux increases with time and the simulation assumes the highest normalized reconnection rate of about 0.06 at \( t = 100 \). This is similar to the Petschek reconnection rate, and it is largely independent of the resistivity model. However, the normalized reconnection rate starts to drop at about \( t = 100 \) and becomes rather small after \( t = 180 \) when a certain amount of magnetic flux has been reconnected. This indicates that the total amount of open flux appears to be limited by the system.

The initial perturbation is not chosen to trigger the KH instability; however, the initial configuration is still KH unstable. Therefore, any fluctuation with a spectrum in the \( y \) direction is expected to generate KH growth as well. In the simulation both magnetic reconnection and KH modes operate simultaneously even though the initial perturbation was chosen to trigger magnetic reconnection. The onset of magnetic reconnection changes the width of the shear flow; thus, it changes the KH instability onset condition. In turn, the evolving KH waves change the width of the current layer, thereby changing conditions for magnetic reconnection.
Figure 3 shows the magnetic field $B_z$ component in the equatorial plane $z = 0$, at $t = 20, 48, 90, 104,$ and $144$ for the reference case. The initial magnetic perturbation leads to the evolution of a thin current layer (diffusion region and attached outflow region) in a limited vicinity of the equatorial plane at $z = 0$ and with a finite extent $|y| \leq 10$ in the y direction. This thinning of the current sheet at $z = 0$ also represents a thinning of the shear flow layer, which changes the KH onset condition. As a result, the fastest growing KH waves are modes with short wavelengths which are unstable only in the thin current sheet region and they are fully developed at about $t = 48$.

The three-dimensional localization is illustrated by the snapshots of the antiparallel ($z$) component of the magnetic field in the center of the initial current sheet in Figure 3. Initially, there are six KH waves in the vicinity of the reconnection diffusion region ($|y| < 10$), which corresponds to a KH wavelength of $\approx 2$. These KH modes are the fastest growing waves, and their instability and growth are determined by the width of the thin shear flow layer [Miura and Pritchett, 1982]. Figure 3 demonstrates the evolution of somewhat longer wavelength KH waves outside of the $y$ range of the diffusion region $|y| > 10$. Their wavelength and growth are determined mostly by the original width of the shear flow layer, which has not yet been effected much by magnetic reconnection. However, the longer wavelength KH modes deform the current layer outside of the initial diffusion region, with localized concentrations (thinning of current layer and thereby triggering the onset condition for magnetic reconnection). Thus, magnetic reconnection also starts to operate outside of the $y$ range in which it has been originally triggered. This newly onset reconnection is similar to reconnection in KH1. Note that the term "diffusion region" here is actually used in an average sense because the initial diffusion region is rapidly split into many small diffusion region parcels through the modulation of the current layer by the KH waves.

The evolution of KH waves from short to longer wavelength KH waves has also been observed by other numerical simulations (see summary in Miura [1995]). This evolution is often considered as the coalescence instability. However, this is not likely the case in the present simulation. Figure 3 illustrates that the longest wavelength KH mode already appears to be the dominant mode at $t = 90$, although shorter wavelength KH modes still exist. This indicates that the shorter wavelength KH modes are being saturated and dissipated instead of undergoing coalescence. At $t = 144$, the longest wavelength mode is identical to the simulation box size in the $y$ direction, which dissipates the current layer and thus suppresses magnetic reconnection.

Figure 4 also illustrates the KH mode expansion along the $z$ direction. At $t = 20$, the largest (but still linear) amplitude KH waves are observed close to the edge of the source region for reconnection. Multiple
nonlinear KH waves with different wavelengths appear at $t = 48$, showing an evolution to longer wavelength KH waves with increasing time, which is consistent with the previous analysis. The figure also demonstrates that these KH waves are localized from $-10$ to $10$ along the $z$ direction. Note that the friction term operates only for $|z| > 30$; such that friction cannot account for the localization. This localization of KH waves is likely caused by the increasing width of the outflow region with distance from $z = 0$, thereby switching off the KH instability or permitting only wavelengths much larger than the width of outflow region. Nevertheless, as illustrated in KH1, this wavelength is limited by the width of KH unstable region along the $z$ direction.

To illustrate the influence of the KH mode on magnetic reconnection, we present the field-aligned electric potential difference, $\Delta \phi$, at $t = 20, 48, 90, 104$, and $144$ for the reference case in a cut at $z = 1$ close to the equatorial plane in Figure 5. The field-aligned electric potential difference is $\Delta \phi = \int E_\parallel ds$, where $E_\parallel$ is the parallel electric field component, and $ds$ is an infinitesimal length along the magnetic field line [Hesse and Schindler, 1988]. The integral is taken along the field line throughout the whole simulation domain from any given point. Figure 5 shows the field-aligned electric potential difference for open field lines at $z = 1$, where a nonzero value indicates that the field line at this location is going through the diffusion region, that is, undergoing magnetic reconnection. The range of the color bar is limited to better represent the structure of the diffusion region. However, we also label the maximum (minimum) value at the top (bottom) of the color bar as a reference. At $t = 20$, magnetic reconnection operates in the initial diffusion region and attached outflow regions with a small field-aligned electric potential difference ($|\Delta \phi| < 0.05$). At $t = 48$, the diffusion region extends through the whole simulation box along the $y$ direction, and its shape is strongly modified by the KH waves. At $t = 90$ and $104$, the open flux region has the same shape of well-developed KH waves or vortices. The largest field-aligned electric potential difference, max $|\Delta \phi|$, appears along the spine of the KH waves instead of the vortex regions. Compared to $t = 104$, the largest field-aligned electric potential difference at $t = 144$ is much higher, which may indicate a field line passing the diffusion region several times due to the periodic boundary conditions or numerical inaccuracy.

In the presence of plasma flow, magnetic reconnection is associated with the generation of field-aligned currents (FACs), which play a critical role in the coupling between the magnetosphere and ionosphere.
Figure 5. Field-aligned electric potential difference at $t = 20, 48, 90, 104,$ and $144$ for the reference case in a cut at $z = 1$ close to the equatorial plane.

[Ma and Otto, 2013]. The generation is basically one-dimensional [Lin and Lee, 1993] and has also been demonstrated in two-dimensional geometry [La Belle-Hamer et al., 1995]. However, the two-dimensional reconnection configuration rules out the KH instability. Nevertheless, the coupling of KH modes and magnetic reconnection should also generate significant FAC. It is demonstrated that the FAC generated by velocity shear is critical for the coupling of the KH waves and current sheet instabilities to the ionosphere [Lysak and Song, 1996]. The two panels of Figure 6 (left) present the magnetic field $B_y$ component and FAC density $j_\parallel$ in the $xz$ plane from a two-dimensional simulation ($y_0 = z_0 = \infty$). It illustrates that the generation of $B_y$ is directly associated with FAC generation [Ma et al., 1995]. In the three-dimensional configuration, this

Figure 6. (left) The two panels show the magnetic field $B_y$ component and FAC density $j_\parallel$ from two-dimensional magnetic reconnection with a perpendicular shear flow. (right) The three panels present the FAC density $j_\parallel$ in a cut at $z = 1$ at $t = 38, 78,$ and $118$ for the reference case.
3.2. Influence of the Shear Flow Magnitude on Reconnection and KH Waves

The solar wind speed is a critical parameter for the evolution of KH waves at the magnetospheric boundary. At 1 AU, the speed of the solar wind is usually around several hundred kilometers per second. Depending on the location, the total velocity difference between solar wind plasma and the stagnant magnetospheric plasma varies from 0 at subsolar point to values close to the solar wind speed near the tailward flank boundary. Figure 7 (top) presents the total open magnetic flux (blue squares, scale on the right side) and maximum normalized reconnection rate (black dots, scale on the left side) for different initial shear flow magnitudes ($M_f \in [0.3, 1]$) without guide field ($B_y = 0$). Both the reconnection rate and total amount of open flux show only a small variation within a larger range of the shear flow velocity. The slightly decreasing maximum open flux with increasing magnitude of the shear flow is likely due to the earlier saturation of KH waves for a faster shear flow. The maximum reconnection rate is largely determined by the amplitude of the nonlinear KH wave rather than the KH growth rate. Although the KH growth rate for $M_f = 1$ is expected to be reduced because the shear flow velocity close to the marginal stability limit, KH waves are still evolving to a nonlinear stage. Therefore, the maximum reconnection rate remains fast. In conclusion, the magnitude of the shear flow plays a minor role for the overall reconnection properties as long as nonlinear KH waves develop. It is also interesting to note that, although the reconnection rate is slightly lower in these cases than in KH1, the total amount of open flux is very consistent with the results in KH1 (Figure 9 in KH1).

Cases with small shear flow ($M_f < 0.3$) are also carried out, and no nonlinear KH waves have been observed on the considered time scale. To illustrate the fundamental difference between magnetic reconnection with and without modulation from nonlinear KH waves, the open magnetic flux of three selected cases are presented in Figure 7 (bottom). The red line represents the reference case; the blue line represents the case with the same parameter as the reference case, except using a box of twice the size in $x$ ($L_x = 60$) and open boundary conditions in the $x$ direction (referred as “large box”). The black line represents a case without shear flow ($M_f = 0$) and the larger simulation domain. Closed boundary conditions in the $x$ direction limit the total flux in the simulation domain that is available for reconnection. This limitation is removed using a larger domain and open boundary conditions (illustrated by the black line). The comparison of the two $M_f = 0.5$ cases shows that the amount of available flux has almost no influence on the saturation of
reconnection observed for nonlinear KH waves. In comparison the $M_f = 0$ case shows that reconnection without KH waves operates slower and does not show the saturation of the magnetic flux.

We also enlarged the simulation domain in the $z$ direction ($L_z = 120$), which allows the KH unstable region along the $z$ direction 3 times the size of the reference case. In this case, the longest wavelength mode develops much earlier and is more dominant than in the reference case (see discussion of three-dimensional stabilization in KH1), which reaches a higher level saturation/maximum open flux of 363. The increase of total amount of flux is likely because the nonlinear KH wave grows to a slightly larger amplitude before saturating for the larger $L_z$ case. This demonstrates that the dominant effect of increasing the size of unstable region in the $z$ direction is the destabilization of KH waves (wavelength $\lambda = 40$ mode), which are marginal nonlinear unstable in the reference case.

### 3.3. Influence of a Guide Field Component on Reconnection and KH Waves

At the dayside magnetopause, a guide field component is present almost everywhere, which usually can be considered as an additional pressure in two-dimensional magnetic reconnection. Nevertheless, this component is parallel to the $k$ vector of the KH waves, which at larger values can stabilize the KH waves. Intuitively, it is expected that reconnection with a guide field which stabilizes KH waves has a similar behavior as reconnection without shear flow. Figure 8 shows the open magnetic flux (Figure 8, top) and normalized reconnection rate (Figure 8, bottom) for three selected cases. The first case (black line) is the reference case; the second case (red line) uses the same parameter except adding a large guide field ($B_{φ0} = 0.5$); and the third case (blue line) has only a guide field ($B_{φ0} = 0.5$) and without shear flow ($M_f = 0$). It is interesting that the case with shear flow and guide field has a similar reconnection rate as the reference case possibly without (or a higher) saturation of the total amount of open flux. This demonstrates that high reconnection rates can also be realized without nonlinear KH modes in the presence of a significant guide field component.

To illustrate the physics for the enhanced reconnection rate with a large guide field, the integral of magnitude of parallel electric field along the $z$ direction, $\int |E_∥| dz$, is evaluated to identify the diffusion region. Figure 9 presents $\int |E_∥| dz$ at $t = 144$ for all the cases in Figure 8 and a case with neither guide field nor shear flow. Figure 9 (third panel) shows that diffusion region is significant modulated by the nonlinear KH waves, and it extends albeit patchy along the $y$ direction for the reference case, while the diffusion region for the case without shear flow and without guide field has a narrow localized diffusion region with a smaller reconnection electric field. In contrast, Figure 9 (second and fourth panels) demonstrates that the diffusion region (or $x$ line) in the cases of large guide fields is spread along the entire length of the simulation domain. This significantly contributes to the large normal reconnection rate even when the local reconnection electric field is in the average lower than in the patchy nonlinear KH case. This spreading of the $x$ line is likely caused by both the guide field and the shear flow. A closer inspection of the reconnection rates for the guide field cases indicates that the observed variation of the normal reconnection rate is at least in part caused by the temporal evolution of the length of the diffusion region. However, once the $x$ line extends through the entire simulation domain (see Figure 9), the normalized reconnection rate is very similar for the guide field cases. It appears that a significant guide field allows the spreading of the diffusion region along the $y$ direction. The mechanism for this process is not well understood, but we note that a guide field allows the propagation of Alfvén waves along the $y$ direction which may also mediate the spreading of the diffusion region. In comparison, the excitation of nonlinear KH vortices provides a very simple mechanism for the spreading of the diffusion region through the thinning of the current layer by the large amplitude boundary waves.
Figure 9. $\int |E_x| \, dz$ at $t = 144$ for selected cases (see context).

The frozen-in condition in combination with the shear flow in the $y$ direction implies a drag of reconnected magnetic field lines into opposite directions on the two sides of the outflow region, which generates a $B_y$ component of opposite polarity in the two outflow regions. This antisymmetry of the $B_y$ component is broken by an initial guide field component, which is fundamentally a two-dimensional effect and illustrated in Figure 10. Figure 10 (left) shows the magnitude of the magnetic field $B_y$ component in a cut at $y = 0$, at $t = 140$ for the $B_{y0} = 0.3$ case. In this configuration (which applies to the dawnside flank of the magnetosphere), the shear flow generates a positive $B_y$ component in the Northern Hemisphere, and

Figure 10. Magnitude of (left) magnetic field $B_y$ component at the $y = 0$ plane and (right) magnetic field $B_y$ component at $z = \pm 2.1$ plane, at $t = 140$ for $B_{y0} = 0.3$ case.
Figure 11. The field-aligned electric potential difference $\Delta \phi$ in a cut at top and bottom boundaries, at $t = 140$ for $B_y = 0.3$ case.

A negative $B_y$ component in the Southern Hemisphere. Therefore, the initial positive guide field component increases the magnitude of $B_y$ in the Northern Hemisphere and decreases the magnitude of $B_y$ in the Southern Hemisphere. Thus, the KH onset conditions are modified by this asymmetric magnetic field $B_y$ component. Figure 10 (right) shows the magnetic field $B_y$ component in the cut at $z = \pm 2.1$. It demonstrates that a long-wavelength, moderate-amplitude KH wave develops in the Southern Hemisphere, while the KH instability is largely switched off in the Northern Hemisphere.

An interesting question is, how does this hemispheric asymmetry affect ionospheric signatures? Figure 11 shows the field-aligned electric potential difference in cuts at the top and bottom boundaries, at $t = 140$ for the $B_y = 0.3$ case. Although the total open flux is the same for both boundaries, the bottom boundary (corresponding to the Southern Hemisphere) shows more vortex structures, which indicates that the guide field component in the IMF may lead to auroral spirals only in one hemisphere.

3.4. Influence of Hall Physics

The typical width of the magnetospheric boundary is about 800–1000 km [Berchem and Russell, 1982; Dunlop et al., 2001], corresponding to 5 to 10 ion inertial scales. The onset condition for magnetic reconnection based on microturbulence requires a width of the current layer comparable or slightly smaller than the ion inertial scale. Based on the above discussion, the wavelength of the KH waves excited in those thin current layers is also comparable to the ion inertial scale. To investigate the influence of Hall physics, we consider a Hall case, in which the width of current layer is 5 ion inertial lengths, (implying $l = 0.4$, see KH1). The Hall term leads to the separation of the ion and electron velocity, and magnetic field lines are frozen to the electron fluid, which carries the majority of the current in thin current sheets. The Geospace Environment Modeling reconnection challenge demonstrated that
the presence of Hall physics increases the two-dimensional magnetic reconnection rate [Birn et al., 2001; Otto, 2001].

Figure 12 presents the open magnetic flux (Figure 12, top) and normalized reconnection rate (Figure 12, bottom) for Hall case (red) and MHD (reference) case (black). It shows that Hall physics leads to a higher normalized reconnection rate at the early stage, but the maximum reconnection rate and the total amount of open flux are close to the MHD case. This indicates that the presence of Hall physics plays a role on small scales of the dynamical process, without a significant difference for overall evolution. Whistler waves generate a finite and much shorter length of the diffusion region along the outflow direction. This implies a higher early reconnection rate because this rate is determined by the width to length aspect ratio as discussed in the various publications of the GEM reconnection challenge [e.g., Birn et al., 2001; Otto, 2001]. Second, in the thin current sheet of the diffusion region, the current is mainly along the y direction and is carried mostly by electrons. Due to the electron frozen-in condition, much of the magnetic structure of the diffusion region is carried by the electrons along the y direction against the current, such that the diffusion region expands fast with the electron motion [Huba and Rudakov, 2002]. This evolution is similar to the spreading of the diffusion region associated with a large guide field. However, the diffusion region in the interaction with KH waves spreads regardless of such that the basic situation is similar to the MHD KH cases. Note also that a fast spreading based on Hall physics is important only when the width of current layer is thin (on the order of the ion inertial scale or thinner), because this corresponds to large current density and fast electron motion.

4. Summary and Discussion

A realistic magnetospheric boundary for southward IMF conditions typically has large antiparallel magnetic field components combined with a large perpendicular shear flow. The combination of large magnetic and velocity shear allows the simultaneous operation of magnetic reconnection and KH modes. Different from our companion paper, KH1, the present study examines the physical properties of this system when reconnection is the primary process. The nonlinear interaction between magnetic reconnection and KH modes is reflected by the modification of the transition layer (i.e., current layer and shear flow layer) width through these two processes. Not surprisingly, and different from the KH trigger used in KH1, reconnection starts immediately and leads to a modification of the current and shear flow layer. KH waves develop self-consistently initially with a rather short wavelength as a result of the thin current sheet and the perturbation generated by reconnection. However, of major importance are the similarities of the nonlinear interaction between the results presented in KH1 and the present study:

1. The normalized (global) reconnection rate is close to the Petschek rate of 0.1, even in the absence of Hall physics when nonlinear KH vortices develop. (1) Strong convergent convection of magnetic flux in the KH spine region generates intense current layers in these regions and (2) the extension of x line or diffusion region perpendicular to the reconnection xz plane. The first mechanism has been discussed in detail in KH1. The second mechanism is naturally occurring in nonlinear KH vortices which generate a chain of intense current layers. However, we also observe a fast extension of the diffusion region in the presence of a significant guide field. In those cases, fast average reconnection rate can occur even in the absence of nonlinear KH waves. The inclusion of Hall physics without the presence of KH waves can also lead to a fast spreading of the diffusion region provided that any initial current layer is sufficiently thin (ion inertial scale). However, in the presence of nonlinear KH waves, average reconnection rates for MHD and Hall MHD are approximately the same.

2. The total amount of open magnetic flux is limited by the longest wavelength mode in the system. It is important to note that in reality, both KH and tearing/reconnection type perturbations are present at the magnetopause. Our study (this paper and KH1) illustrates that even the system is initialized by different dynamical processes, the saturation of the total amount of open magnetic flux by the largest scale nonlinear KH wave is the same. To some degree, this indicates that the dominance of the KH wave interaction which forces magnetic reconnection even in cases where the interaction is started by the reconnection process.

Our results demonstrate that magnetic reconnection can seed the KH mode for KH unstable conditions. In KH1, it is demonstrated that the wavelength of a three-dimensional KH wave is limited by the localization along the third direction. The present study demonstrates that the early KH wavelengths are largely modulated by magnetic reconnection, which may provide an explanation of irregular KH modes in the
observational results by Hwang et al. [2011]. Shear flow layer thinning in the reconnection diffusion region generates short wavelength KH waves, while widening in the reconnection outflow region allows only longer wavelength KH waves or may switch off the KH instability at large distances from the diffusion region. The growth of longer wavelength KH waves is subject to the constraint of the localization in the vicinity of the equatorial plane (z direction). At the actual magnetopause, KH modes do not occur as a result of an initial value problem but as a boundary value problem, such that a growth time should be interpreted as a growth length and time translates into distance from the subsolar magnetopause.

Our results suggest that the presence of fairly short KH waves close to the subsolar region if reconnection operates in this region and at a distance where the sheath slow is sufficiently fast to render the boundary KH unstable. Note that short wavelengths correspond to small growth times and short growth distances. The evolution from short to long wavelength modes can occur by coalescence or dissipation of short wavelength modes and ordinary growth and later dominance of longer wavelength modes as illustrated by our results.

Our results also examine the onset conditions for the interaction between magnetic reconnection and KH modes. It is demonstrated that a low magnitude of shear flow is sufficient for nonlinear KH waves and high reconnection rates (subject to any stabilization by a guide field). At the Earth's magnetopause (i.e., low plasma beta conditions), this is easily exceeded a small distance from the subsolar point. It is interesting that the fastest normalized reconnection is fairly insensitive to the shear flow magnitude within the range of unstable KH configuration. The fastest reconnection rates are achieved by a nonlinear amplitude of the KH waves rather than the growth rate. Large amplitude waves imply enhanced convergent convection at the KH spine region and thereby amplify the current density in these regions.

It is well known and confirmed by our results that a sufficiently guide field can stabilize the KH instability. In addition, a guide field leads a hemispheric asymmetry, because reconnection in the presence of shear flow generates a magnetic field $B_y$ component with opposite polarity in the two outflow regions. The superposition of a guide field therefore causes an asymmetric $B_y$, in the Northern and Southern Hemispheres which is associated with asymmetric field-aligned currents. This effect may influence conjugate auroral observations. Furthermore, the saturation of the total amount of open flux is removed when the KH mode is stabilized by a sufficient large guide field component. The presence of a guide field component may also extend the x line and increase the normalized reconnection rate.

In conclusion, the presented study provides a comprehensive understanding of the nonlinear interaction between magnetic reconnection and KH modes. Nevertheless, there remain some important open questions. Our study treats the KH/reconnection interaction as an initial value rather than a boundary value problem with the advantage of high local resolution. The only alternative treatments of boundary layer problems are global simulations which suffer from much lower resolution and therefore enhanced numerical dissipation. There is currently only little evidence that short wavelength KH waves can be excited close to the subsolar region. However, if this were the case, kinetic effects can play an important role if these waves develop on very short kinetic or inertial scales. Another aspect of outstanding future work is a detailed comparison between simulation and observation results, i.e., what are the typical observational signatures of KH modulated magnetic reconnection? As mentioned in KH1, the dominant reconnection operates in the spine region; therefore, the typical reconnection observational signature, that is, fast jet and rotation of the magnetic field into the shear flow direction, is expected to be found in that region. It should be noted that reconnection in KH spine regions should also produce significant deflections of the boundary normal directions. Inside of KH vortices, a satellite may intersect several current layers. Overall, the patchy nature of the diffusion regions generated by the KH waves can be expected to lead to FTE-like signature away from the equatorial plane.

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