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Dependence of the magnetopause Kelvin-Helmholtz instability on the orientation of the magnetosheath magnetic field

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Abstract. It is shown by means of a 2-D MHD simulation that the observed rotation of the unperturbed magnetic field within the magnetopause (MP), which is assumed to be a tangential discontinuity (TD), leads to a significant dependence of the magnetopause Kelvin-Helmholtz (K-H) instability on the orientation of the sheath field. That is, northward sheath B_z is more favorable to the instability than southward B_z and the MP undulates most strongly when the sheath field points due north. When the sheath field does not point due north, a slow rarefaction region is formed in the velocity boundary layer (BL) inside the MP, wherein there are minima of the plasma pressure and temperature accompanied by a maximum of the magnetic pressure.

Introduction

The MP is susceptible to the K-H instability, which is driven by the velocity shear at the MP. The instability is an important source of tangential drag (stress) at the MP [*Miura*, 1984], which is responsible for a tailward stretching of field lines. Although previous work [*Miura*, 1984] shows that the instability depends on whether the flow is parallel or perpendicular to the field, the dependence of the magnetopause K-H instability on the orientation of the sheath field has not been fully understood. The preliminary results of the present study have been discussed [*Miura*, 1995] and the purpose of the present paper is to investigate in more detail the dependence of the instability at the MP as a TD and the structure of the velocity BL on the orientation of the sheath field.

Model of the Magnetopause

In the present model, the magnetosheath flow and magnetic field are characterized by $M_S=V_0/C_S$, $M_A=V_0/V_A$ and θ_{sh}, where V_0 is the total jump of the tangential flow velocity across the MP, C_S and V_A are the sound and Alfvén speeds in the sheath, and θ_{sh} ($=\cos^{-1}(B_{0zsh}/B_{0sh})$) is the polar angle of the sheath field measured from the z-axis pointing due north. Here, B_{0zsh} is the z component of the unperturbed sheath field and B_{0sh} is the strength of the unperturbed sheath field. The plasma β in the magnetosphere β_{sp} is fixed to 0.2. The length of the simulation box along the unperturbed flow is fixed to 15.7a, nearly equal to the wavelength of the linearly fastest growing mode, where a is one-half of the thickness of the velocity shear layer. The periodicity is assumed in the flow direction.

Figure 1 shows a configuration across the low latitude MP boundary of the unperturbed flow velocity (left) and magnetic field (right). They are specified as follows:

$$v_{0y}(x) = (V_0/2)[1 - \tanh(x/a)] \quad (1)$$

$$B_{0y}(x) = B_0(x) \sin(\theta(x)) \quad (2)$$

$$B_{0z}(x) = B_0(x) \cos(\theta(x)) \quad (3)$$

where

$$B_0(x) = |B(x)| = B_{0sh} + 1/2(B_{0sp} - B_{0sh}) [1+\tanh(x/a)] \quad (4)$$

$$\theta(x) = (\theta_{sh}/2)[1 - \tanh(x/a)] \quad (5)$$

Here, x is the direction normal to the unperturbed MP and B_{0sp} and B_{0sh} are the field strength at $x = \infty$ and $x = -\infty$. The unperturbed pressure is chosen so that it satisfies the pressure balance. The rotation of the unperturbed field within the MP as a TD as described above has been observed [e.g., *Sonnerup and Ledley*, 1979]. Although the MHD description of the TD, (1) – (3), cannot specify how the current can be carried by two plasma species, a self-consistent kinetic model of the TD with arbitrary field rotation can be constructed based on Vlasov-Maxwell equations [e.g., *Roth*, 1979]. For a rotational discontinuity *Swift and Lee* [1983] have shown by kinetic simulations that the field rotation occurs within the MP so as to minimize the total rotational angle. Since the actual MP has a thickness of several ion Larmor radii, the MHD simulation of the magnetopause K-H instability is useful, if not complete. Several important features of the MHD K-H instability have been reproduced by kinetic simulations with the thickness of the velocity shear layer comparable to a few ion Larmor radii [*Thomas and Winske*, 1993; *Fujimoto and Terasawa*, 1994; *Wilber and Winglee*, 1995]. The proton temperature in the magnetosphere is higher than that in the sheath. However, the unperturbed temperature is taken uniform in the present study for simplicity. Figure 2 shows a hodogram representation of the transition of an unperturbed field from the magnetosheath (represented by *sh*) to the magnetosphere (represented by *sp*) in the y–z plane parallel to the unperturbed MP for three θ_{sh}, i.e., 0° (left), 90° (middle), 180° (right) and for $M_S = M_A = 1$. The field strength in the sheath adjacent to the MP is mostly comparable or even stronger than that in the magnetospheric side. This is particularly so, when the sheath field is northward and the depletion layer is formed outside the MP. But this effect is not taken into account in the present simulation.

Simulation Results

The 2-D MHD simulations in the x-y (equatorial) plane have been performed for seven θ_{sh} and three M_A. In all runs M_S was fixed to 1.0. For all parameters the MP was unstable. Figure 3 shows linear growth rates calculated from the linear growth in the initial phase of each simulation run as a function of θ_{sh} for three M_A. For all M_A the linear growth rate is largest when the sheath field points due north. This is due to the disappearance of B_{0y}, the stabilizing component of the unperturbed field parallel to the undisturbed flow, or due to the disappearance of $\mathbf{k}\cdot\mathbf{B}_0$ responsible for a field line bending, where $\mathbf{k}$ is the wave vector in the y – z plane. The growth rate is larger for larger M_A when the sheath field is northward but not due north. This is explained by the fact that for larger M_A the stabilizing B_{0y} is smaller. Figure 3 shows that there is significant dependence on θ_{sh} of the magnetopause K-H instability. For most parameters, northward B_z is more favorable to the instability than southward B_z and the larger momentum transport occurs for northward sheath B_z (see *Miura* [1995]).

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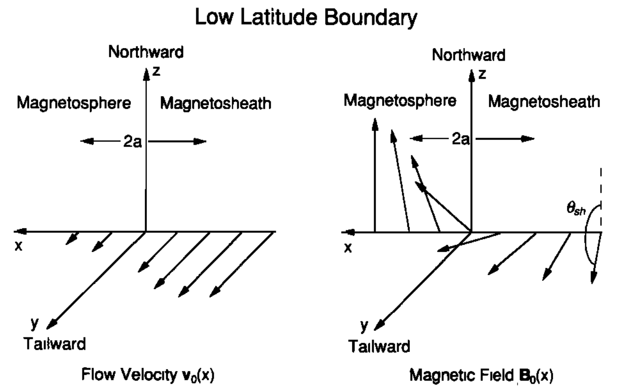

Figure 1. Model configuration of the unperturbed flow velocity (left) and unperturbed magnetic field (right) across the low latitude MP boundary. θ_{sh} is the polar angle at $x = -\infty$ of the sheath field, which is measured from the z-axis.

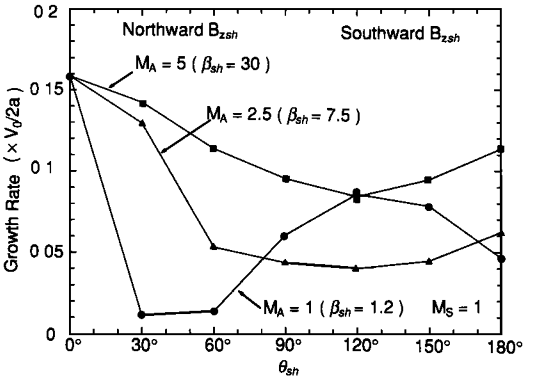

Figure 3. Linear growth rates of the K-H instability as a function of θ_{sh} for three M_A and for a fixed M_S=1.

Figure 4 shows contour plots of plasma pressure for three θ_{sh} , i.e., 0° (top), 90° (middle), and 180° (bottom) in their saturation stages. For all runs M_A = 2.5 was used. Arrows indicate the direction of the sheath flow. The steep pressure gradient corresponds to the MP current layer. For θ_{sh} = 0° the magnetopause undulates most strongly. For θ_{sh} = 90° the MP remains almost straight in spite of the fact that the MP is unstable, because the strong tension associated with the flow-aligned unperturbed field at $x < 0$ inhibits a large MP undulation. However, in this case the pressure inside the MP is perturbed by the instability. For θ_{sh} = 180° the MP undulates slightly owing to the strong tension associated with the flow-aligned unperturbed field near x~0. A similar pressure perturbation as observed for θ_{sh} = 90° can also be seen for θ_{sh} = 180° inside the MP. In these panels the density or pressure BL, wherein the density or the pressure changes from its sheath value to the magnetospheric value, is not widened, but rather the BL seems to be constricted by the instability. This suggests that the thickness of the low latitude BL, conventionally characterized by the density gradient [*Eastman et al.*, 1976], does not change with the instability, but the velocity shear layer inside the MP is widened (see Figure 5).

The left panel of Figure 5 shows, from the top, profiles as a function of x the convection electric field E_x, three components of the flow velocity, three components of the magnetic field, the density ρ, the temperature T, the magnetic pressure $B^2/2\mu_0$, the plasma pressure P, the total pressure Pt (the sum of the magnetic and plasma pressures), and the plasma β at y = 9.42a and T= 30 for θ_{sh} = 0°, M_A = 2.5. The flow velocity is normalized by V_0 and the magnetic field is normalized by the peak field strength at y = 9.42a. The density, temperature and pressure are normalized by their values at $x = -\infty$ in the sheath. The total pressure and the magnetic pressure are normalized by their peak values at y=9.42a. The dotted profiles in this panel represent those profiles at the initial stage. The MP in this panel is the magnetopause defined as the outer edge of the MP current layer. The density BL is a boundary layer characterized by the density gradient and the velocity BL is a boundary layer characterized by the gradient of the tailward flow velocity (v_y). The middle panel shows the same profiles at T=90 and y=13.5a for θ_{sh} = 90° and M_A = 2.5. The right panel shows the same profiles at T=60 and y=7.85a for θ_{sh} = 180° and M_A = 2.5. For the sheath field due north (left panel) a wide velocity BL is formed inside the MP due to the transport of the tailward flow momentum into the magnetosphere. The total pressure is slightly peaked near the MP. This means that the dynamic pressure is not negligible where the total pressure has a deficit. Notice in the right panel that the pressure minimum in the region between vertical dashed lines is associated with a maximum of the magnetic pressure, which is larger than that in the adjacent regions. The plasma temperature also has a minimum in this region. The tailward flow velocity v_y is also peaked (accelerated) here due to the increase in the absolute value of E_x. A wide velocity BL is formed inside the MP. In this case Pt has a small deficit near the MP. This means that the force, which is due to the total pressure gradient in the velocity BL and is directed toward the MP, is balanced by the tension force, directed toward the magnetosphere, of the curved field lines,

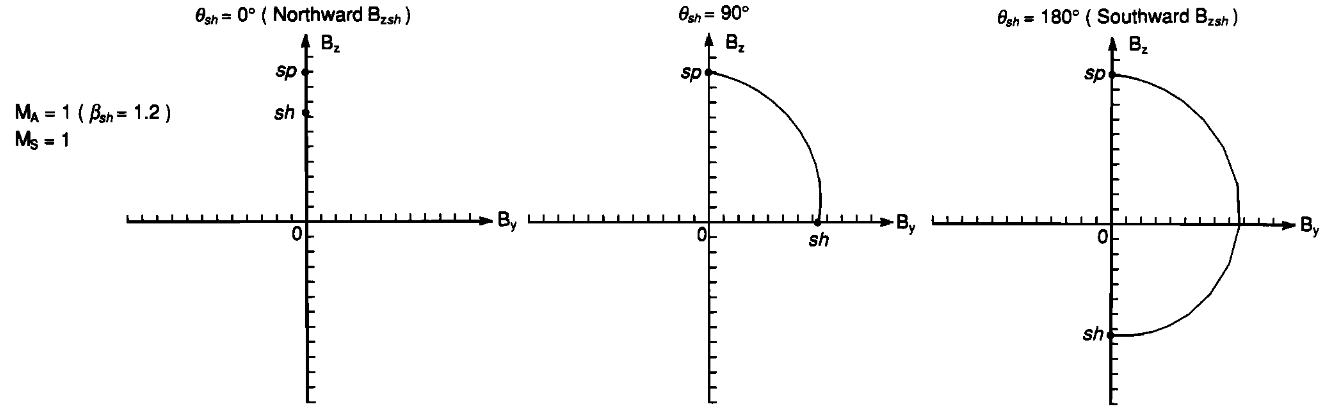

Figure 2. Hodogram representation (y-z plane) of the transition of the unperturbed field from the magnetosheath (represented by *sh*) to the magnetosphere (represented by *sp*) for three θ_{sh}. Here, the positive y points tailward and the positive z points northward.

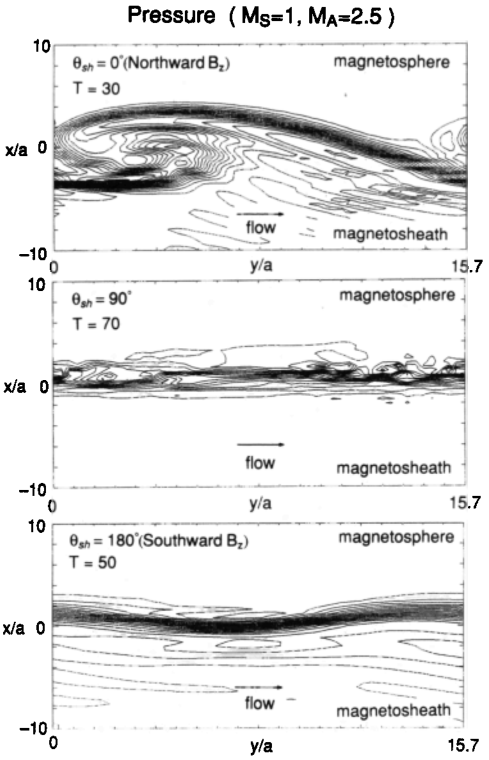

Figure 4. Contour plots of the plasma pressure at the saturation stage for three θ_{sh}, and for M_A = 2.5 and M_S =1.0. Arrows indicate the direction of the sheath flow.

which are convex outward from the magnetosphere. This tension is responsible for a constriction of the flux tube in the velocity BL and consequent plasma pushing parallel to the field line, which results in a field maximum and a pressure minimum in the flux tube. The right panel shows that the pressure deficit in the pressure minimum is about $P_0/5$, where P_0 is the unperturbed plasma pressure in the sheath. By assuming that the pressure gradient due to this pressure deficit is maintained over the distance of 15.7a/4 along the field line (see pressure contours inside the MP in the bottom panel of Figure 4), the pressure gradient force parallel to B_{0y} at $x \sim 0$ becomes $0.1 \cdot P_0/(2a)$. Such a pressure minimum and a field maximum are more evident in the region between the vertical dashed lines in the middle panel, where the development of the instability is weaker, and they are associated with minima in temperature and density. The tailward flow (v_y) is slightly accelerated and a substantial v_z appears in this region. In this case Pt remains almost constant inside the MP because the MP boundary remains almost straight (see the middle panel in Figure 4) and, therefore, the tension due to the field line curvature is not produced. Since these regions between the vertical dashed lines are characterized by a diamagnetic structure (anti-correlation between the pressure and the magnetic pressure) and a decrease in the temperature, these regions are slow rarefaction regions. Such a slow rarefaction region is not observed in the left panel, as the field lines remain straight for θ_{sh} = 0° in the present 2-D simulation and hence there is no tension due to the bent field line, which is responsible for a constriction of the flux tube. Therefore, the magnetopause K-H instability, when the sheath field is not due north, leads to a formation of the slow rarefaction region in the velocity BL. The formation of a slow rarefaction region by the instability in a uniform plasma was first demonstrated by a 2-D MHD simulation [*Miura*, 1984].

Discussion and Conclusions

The present results showing a stronger development of the magnetopause K-H instability for the northward sheath field at least for M_A greater than 2.5 (see Figure 3) seem to be able to explain the occurrence of well developed boundary waves on the flank MP during the IMF positive B_Z [*Chen et al.*, 1993; *Chen and Kivelson*, 1993; *Kokubun et al.*, 1994; *Kivelson and*

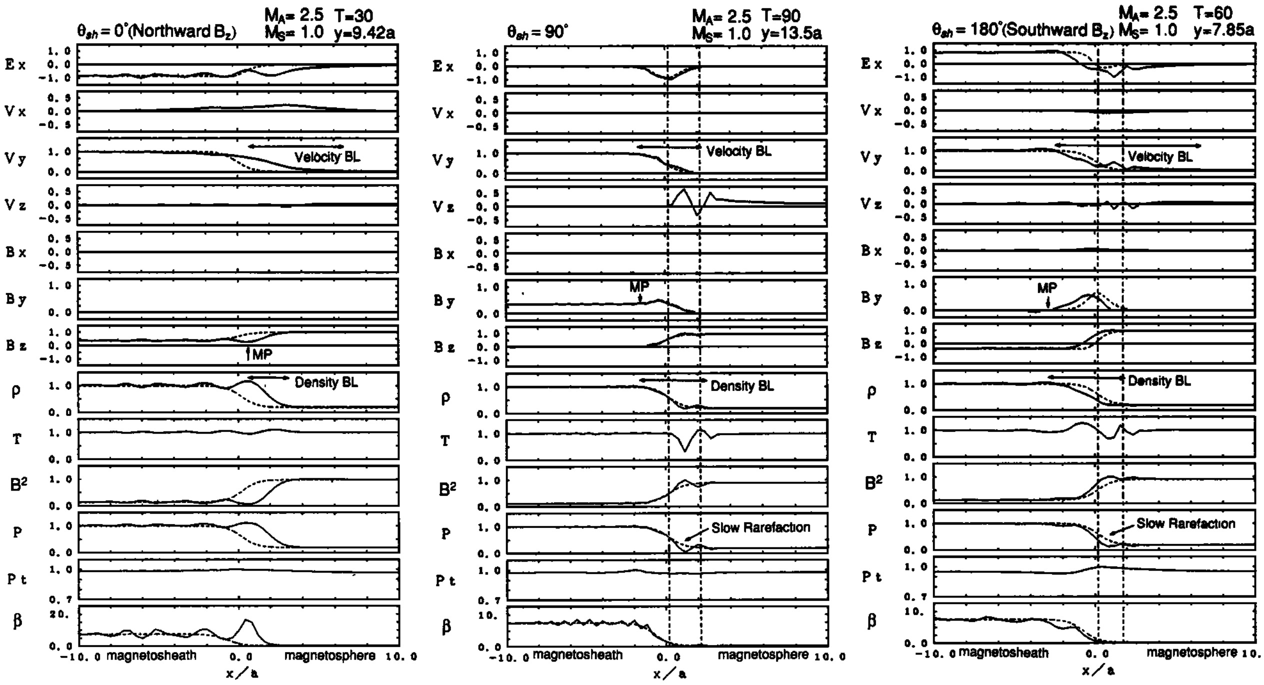

Figure 5. Profiles of MHD quantities as a function of x (across the MP) for T = 30, θ_{sh} = 0°, M_A = 2.5, M_S =1.0 (left), T = 90, θ_{sh} = 90°, M_A = 2.5, M_S = 1.0 (middle) and for T=60, θ_{sh} = 180°, M_A = 2.5, M_S =1.0 (right). Dashed curves are those profiles at the initial stage. The MP is the magnetopause defined as the outer edge of the magnetopause current layer. The velocity BL and the density BL are indicated by arrows. The regions between vertical dashed lines in the middle and the right panels are slow rarefaction regions.

Chen, 1995], although *Kivelson and Chen* [1995] note carefully that their sample (four cases with the positive B_Z out of five events) is too small to prove a positive correlation between the well developed boundary waves and the IMF positive B_Z. The observation of multiple MP crossings with Geotail for southward sheath B_Z in the dawn flank sector [*Mozer et al.*, 1994; *Kawano et al.*, 1994] may also not contradict the present finding that the MP is also unstable for southward sheath field orientation. *Mozer et al.* [1994] and *Kawano et al.* [1994] found that the magnetic field was larger and the plasma density was smaller in the low latitude BL than they were in the sheath or in the magnetosphere. Such an observation of the field maximum and the pressure minimum in the low latitude BL has also been reported by *Hall et al.* [1991] for southward sheath field orientation and by *Sonnerup et al.* [1992]. The formation of a slow rarefaction region in the velocity BL by the K-H instability, when the sheath field is not due north, provides a simple explanation of such a field maximum accompanied by a pressure or density minimum in the low latitude BL. For the case with northward sheath field (the top panel in Figure 4), the steepening slope is located at the upstream side in contradiction of an observation by *Chen and Kivelson* [1993], who showed that the steepening slope is located at the downstream side. As *Chen and Kivelson* [1993] suggest, this abnormal steepening is possibly due to the tension of the sheath field lines, which is a 3-D effect not included in the present 2-D simulation. The observed long wavelength (~$15R_E$) of the boundary wave [*Chen et al.*, 1993] comparable to the magnetospheric radius may also indicate that the global shape of the magnetosphere must be taken into account in the study of the instability.

Since the control of the K-H instability by the sheath B_Z, found in the present study, stems from the initial field configuration that was assumed arbitrary to model the observations within the MP, which is assumed to be a TD, applications of the present results are justified only when these assumptions are validated. It should also be mentioned that the observed less active K-H instability for negative B_Z could result from losing the competition with the reconnection process.

The present results help identify physical processes at the MP by studying their dependence on the sheath field orientation. In view of the fact that the flow acceleration near the MP has mostly been ascribed to the MP reconnection, the flow acceleration observed in the slow rarefaction region produced by the K-H instability merits further investigation for possible application in a variety of plasma boundaries and interfaces in space plasmas.

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