GEOPHYSICAL RESEARCH LETTERS, VOL. 12, NO. 10, PAGES 635-638, OCTOBER 1985

KELVIN-HELMHOLTZ INSTABILITY AT THE MAGNETOSPHERIC BOUNDARY

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Abstract. A magnetohydrodynamic simulation of Kelvin-Helmholtz instability at the magnetospheric boundary is performed by including inhomogeneities of plasma and magnetic field at the dayside low latitude magnetospheric boundary. A magnetopause current layer is corrugated highly nonlinearly by the instability and a wide velocity boundary layer is formed within the magnetopause current layer, a result being consistent with observations. Interchange of plasma and flux tubes is accomplished by the instability.

Introduction

It has long been suggested that the solar wind plasma flow interacts with magnetospheric plasma in two basic ways: one is the viscous-like interaction (Axford and Hines, 1961) along the flanks of the magnetosphere and the other is the reconnection of the interplanetary magnetic field lines with the terrestrial magnetic field lines (Dungey, 1961; Petschek, 1964; Levy et al., 1964). In the viscous-like interaction model the solar wind momentum diffuses onto the magnetosphere via 'anomalous viscosity' through the magnetospheric boundary. In order to explain the observed magnetospheric convection the viscosity at the magnetospheric boundary must be essentially 'anomalous', since the actual ion-ion viscosity by Coulomb collisions at the boundary is negligibly small to explain the required momentum transport. It has recently been demonstrated (Miura, 1982, 1984) by a magnetohydrodynamic (MHD) simulation that the MHD Kelvin-Helmholtz (KH) instability driven by velocity shear existing at the magnetospheric boundary is a fundamental mechanism yielding required anomalous momentum and energy transport and hence the anomalous (eddy and magnetic) viscosity for the viscous interaction hypothesis of Axford and Hines (1961). In that simulation, however, the inhomogeneities of plasma and magnetic field at the magnetospheric boundary were not included and hence the magnetospheric boundary has not been properly modelled; the purpose of this letter is therefore to extend that simulation model to a more realistic configuration including those inhomogeneities of plasma and magnetic field at the boundary, especially at the dayside low latitude boundary, and hence to provide a more realistic modelling of the KH instability at the magnetospheric boundary. Such a realistic simulation of the KH instability at the magnetospheric boundary is an important step toward a complete understanding of the nature of the viscous interaction at the boundary and the resulting boundary structure.

In the present simulation we assume that a magnetospheric boundary is a 'finite thick tangential discontinuity', because the magnetopause current layer and the velocity shear layer at the boundary are at least several finite Larmor radii thick (e.g., Parker, 1967; Berchem and Russell, 1982); also an initial-value treatment of the Helmholtz instability is improperly posed for the velocity shear layer of zero thickness (Richtmyer and Morton, 1967); such a tangential discontinuity is at times observed on the dayside magnetospheric boundary (Papamastrakis, et al., 1984). We adopt a 2-D model, which seems to be a good assumption as long as the condition $\gamma_{KH} \tau_W >> 1$ is satisfied, where γ_{KH} is the growth rate of the KH instability and τ_W is the travel time of the Alfvén wave propagating from the magnetopause to the ionosphere and returning back to the magnetopause after reflection from the ionosphere. Finally we assume that the initial velocity shear layer and the magnetopause current layer have same thicknesses; by starting from the same thickness of the two layers we will then be able to elucidate how the two layers evolve with time and what kind of boundary structure is realized by the KH instability.

Model

Figure 1 shows a model of the finite thick tangential discontinuity representing the dayside low latitude magnetospheric boundary on the equatorial plane. The magnetospheric boundary is characterized by the shear in the flow velocity, the magnetic field change, and the gradient of the plasma density: The magnetosheath plasma is flowing with the velocity V_o and the magnetospheric plasma is stationary with a transition represented by a hyperbolic tangent shear profile. The magnetic field (solid arrows) in the magnetosheath is taken parallel to the flow (dashed arrows). In order to represent that both flow velocity and magnetic field are sheared in a thickness 2a we express the flow velocity $v_{oy}(x)$ and y and z components of the magnetic field as follows:

$$v_{oy}(x) = (V_o/2)(1 - \tanh(x/a)) \quad (1)$$

$$B_{oy}(x) = (B_o/2)(1 - \tanh(x/a)) \quad (2)$$

$$B_{oz}(x) = 5.08\cdot(B_o/2)(1 + \tanh(x/a)) \quad (3)$$

The plasma pressure $p_o(x)$ is taken to satisfy the total pressure balance. The plasma temperature is assumed uniform across the boundary. In the magnetosheath the Alfvén mach number $M_A = 5.0$ and the sound mach number $M_s = 1.0$, where $M_A = V_o/v_A$ and $M_s = V_o/c_s$, v_A and c_s being the Alfvén speed and the sound speed, respectively, and the plasma β ($\beta = 2\mu_o p_o/B_o^2$) is 30. The plasma β in the magnetosphere is 0.2. A periodic boundary condition is imposed at y = 0 and y = L_y and hence the KH instability is absolute in the present model. The periodicity length L_y in the y direction is set nearly equal to the wavelength of the fastest growing mode 15.7a. Time is normalized by a/V_o. The detail of the numerical scheme used is described by Miura (1985).

Paper number 5L6611.
0094-8276/85/005L-6611$03.00

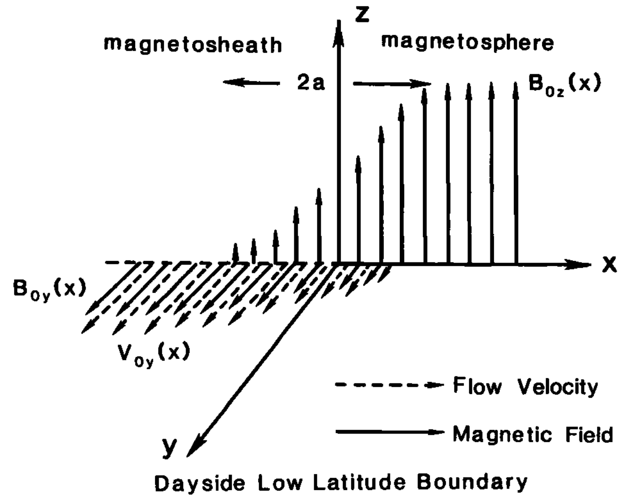

Fig. 1. A model of the finite thick tangential discontinuity representing the dayside low latitude magnetospheric boundary.

Results

Starting from the initial equilibrium specified in the previous section a MHD simulation has been performed by adding a small unstable perturbation to the initial flowing equilibrium. The KH instability has grown linearly and saturated at T = 70. Figure 2 shows flow velocity vectors (left panels) and magnetic field vectors (right panels) at T = 20 and 80. The flow is found to be disturbed more and more with time and at T = 80 the initial parallel shear flow is disturbed very strongly; by this time the gradient of the flow velocity has been diffused quite remarkably and a large flow in the positive y direction (antisunward) is induced in the region x < 0, which was originally the stationary magnetosphere. This formation of the wide velocity shear layer from the initially narrow shear layer is due to the anomalous momentum transport by the KH instability. The current layer also undulates with time and at T = 80 the magnetic field lines in the magnetosheath are strongly stretched and twisted, and the magnetopause current layer is corrugated highly nonlinearly. In contrast to the flow evolution shown in the left panels, where the velocity gradient has been diffused remarkably by the instability, the magnetopause current layer characterized by a steep gradient of the magnetic field has still a clear cut field gradient. This is because in the present ideal magnetohydrodynamics the KH instability gives the anomalous viscosity but not the anomalous resistivity, which is necessary to diffuse the magnetopause current layer.

Shown in Figure 3 are 3-D views of top surfaces of the plasma pressure for four different times in the temporal evolution. The boundary is seen to be undulated with time and at T = 80 we see that the magnetopause boundary characterized by a steep gradient of the plasma pressure is deformed in a very complicated, highly nonlinear manner to form a plasma blob within the magnetospheric boundary as a result of the interchange motion. These panels demonstrate clearly how the plasma of the high pressure side (magnetosheath) tends to penetrate into the low pressure side (magnetosphere) owing to the KH instability.

Three panels in Figure 4 show cross-sectional profiles, as a function of x, of E_x, the plasma β, the density ρ, the temperature T, v_x, v_y, B_z, B_y,

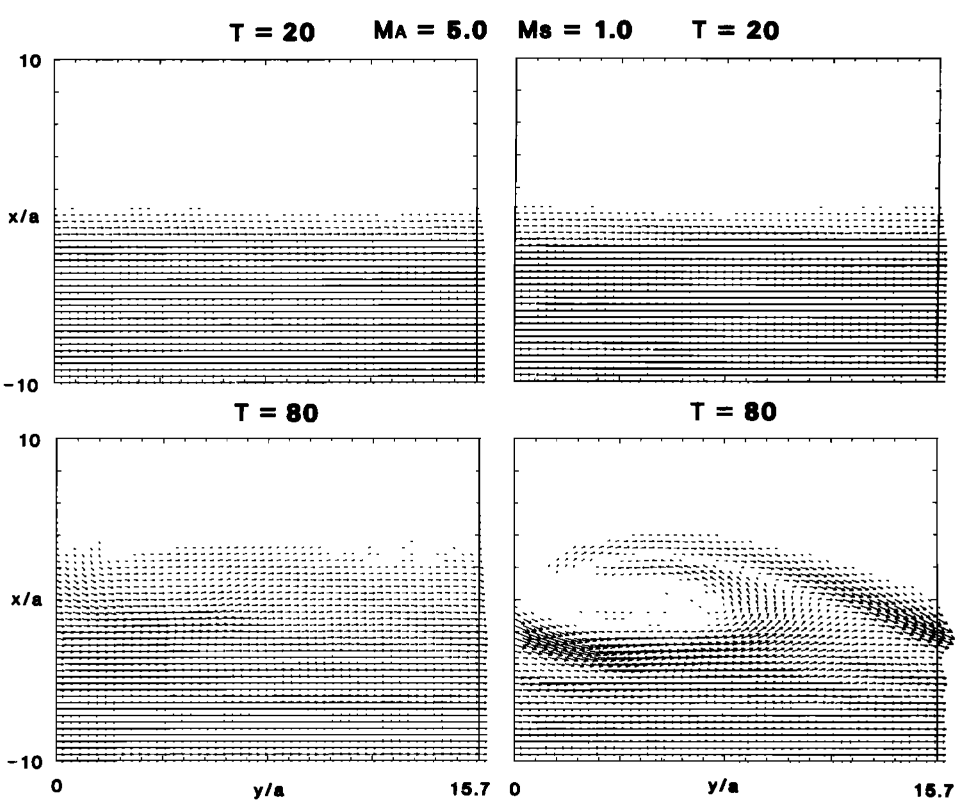

Fig. 2. Flow velocity vectors (left panels) and magnetic field vectors (right panels) at T = 20 and 80.

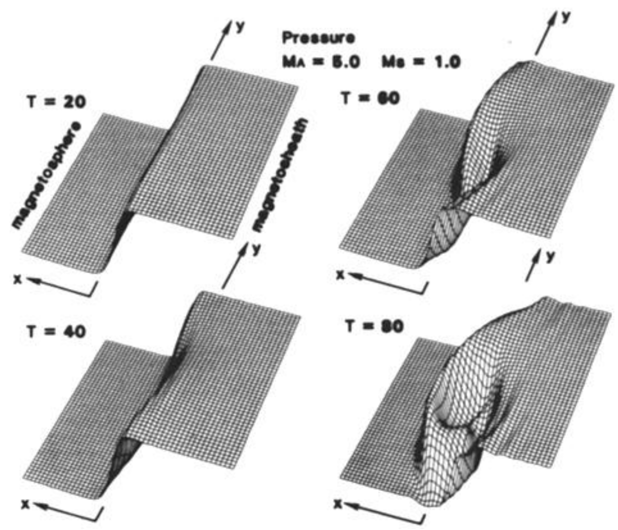

Fig. 3. 3-D views of top surfaces of the plasma pressure at T = 20, 40, 60, and 80.

B_x, $|B|$, and the pressure p at T = 80 for three different y(y/a = 5.97, 12.2, 15.4 from the left panel); the dotted curves in these panels show initial profiles of those MHD variables; the variables are so normalized that only relative scales are meaningful. In the leftmost panel at y = 5.97a, those profiles of MHD variables across the plasma blob are shown: In this panel we identify three magnetopause regions (designated as MP), which are characterized by a steep gradient of B_z or p and distinguish between a region of high-β magnetosheath plasma and a low-β magnetospheric plasma. The magnetopause is shifted by a large distance by the KH instability. In the profile of v_y in this panel, we see the existence of a reverse flow at $4 \le x/a \le 9$, which corresponds to the region where a flow vortex is formed. In the middle panel the magnetopause is shifted slightly and a very wide velocity boundary layer (hatched region) is formed inside the magnetopause current layer; the width of this velocity boundary layer is much larger than the initial thickness of the magnetopause current layer and the velocity shear layer. In the rightmost panel the magnetopause is again shifted, and a wide velocity boundary layer is formed inside the magnetopause current layer. The formed boundary layer is several times thicker than the magnetopause current layer. In contrast to the large diffusion of v_y due to the anomalous momentum transport by the KH instability, the gradient of B_z at the magnetopause is found to become slightly steeper than the initial gradient (dotted line) and this means that the magnetopause current layer is constricted by disturbed converging flows. In this regard it is also of interest to notice that the plasma is heated and cooled adiabatically by magnetosonic compression and rarefaction.

Discussion

The present result seems to be consistent with observations of Eastman and Hones (1979) showing the existence of a layer of substantial antisunward flow within the magnetopause current layer, whose thickness is much larger than the magnetopause thickness typically equal to $\sim 10\rho_{Li}$ (Berchem and Russell, 1982). Here one quantity which is of interest for comparison with observations is the ratio of the thickness of the velocity boundary layer to the thickness of the magnetopause current layer. The present simulation indicates (see Figure 4) that the thickness of the velocity boundary layer just inside the magnetopause current layer is modulated by the KH instability, a result being consistent with observations (Sckopke et al., 1981), and that the average of the final thickness of the velocity boundary layer is 4-5 times of the

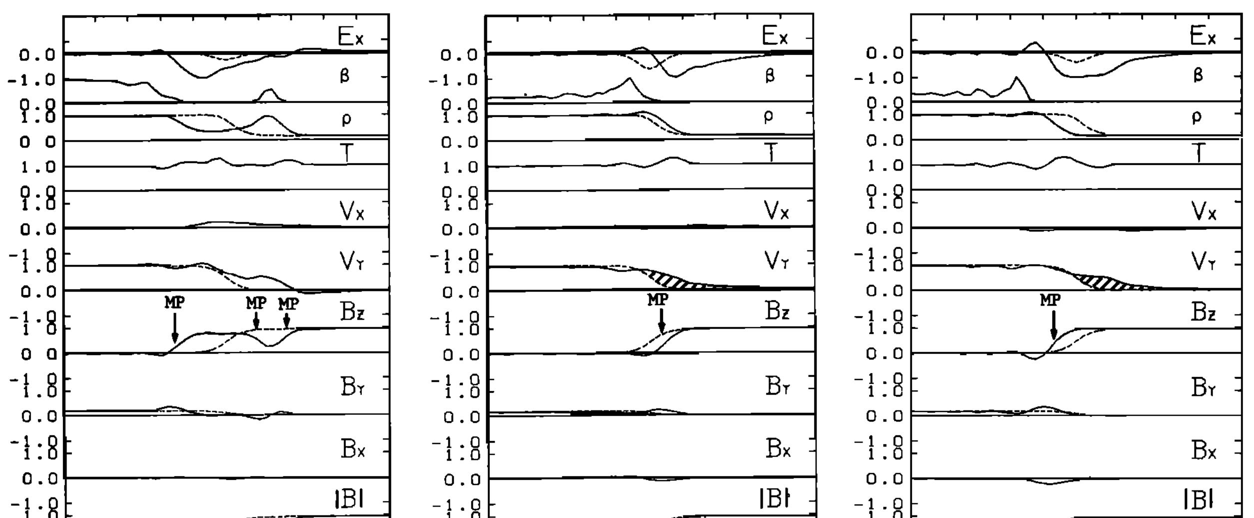

Fig. 4. Cross-sectional profiles, as a function of x, of E_x, the plasma β, the density ρ, the temperature T, v_x, v_y, B_z, B_y, B_x, $|B|$, and the pressure p at T = 80 for y/a = 5.97, 12.2, 15.4 from the left panel; the dotted curves are initial profiles of those MHD variables; MP is the magnetopause current layer and the velocity boundary layer within the magnetopause current layer is hatched.

thickness of the magnetopause current layer, which has remained almost constant during the evolution of the KH instability. The above ratio seems to be still smaller compared with the observed average value ∿25 (Eastman and Hones, 1979). The reason of this may be that in the present simulation we have taken initial thickness of magnetopause current layer and the velocity shear layer equal; in the actual dayside region, where the KH instability is initiated, those thicknesses may well be different at the outset. Another quantity, which is also of interest in evaluating the contribution of the KH instability to the magnetospheric convection, is the convection potential (not necessarily electrostatic potential) drop across the boundary layer defined by $\int E_x dx$. The ratio of this integral of the electric field to its initial value has been calculated for three different cross sections shown in Figure 4 and we obtained those ratios of 5.68, 2.75, 5.48 from the left panel; thus the antisunward convection potential drop (strength) is amplified several times by the anomalous momentum transport associated with the KH instability. The anomalous (eddy and magnetic) viscosity obtained for the present case is comparable to that obtained for the homogeneous case (Miura, 1984), i.e. $\nu_{ano} \sim 0.01\ aV_0$, and thus sufficient for the viscous interaction hypothesis of Axford and Hines (1961).

Let us assume that 2a = 1000 km - 3000 km and V_0 = 300 km/sec. Then we obtain the wavelength $\lambda = 16 \times 10^3$ km - 47×10^3 km, the wave period τ = 107 sec - 313 sec. These are comparable to the wavelength and the wave period typical of the boundary wave observed on the magnetopause boundary (e.g., Lepping and Burlaga, 1979; Aubry et al., 1971). Using the e-folding distance $\ell_e = (1/\gamma_{KH})(\omega_r/k)$ we obtain $\gamma_{KH}\tau_d = (1/2)(\ell/\ell_e)$, where ℓ is the distance from the subsolar point to the dawn or dusk flank and τ_d is a dynamical time scale, which is required for the magnetosheath flow to travel from the subsolar point to dawn or dusk flank. Since $\ell_e \sim \lambda$ (Miura, 1984) and $\lambda \ll \ell \sim 15\ R_e$, we obtain $\gamma_{KH}\tau_d \sim 4$; therefore the KH instability develops fast enough along the magnetospheric boundary to impose a substantial tangential stress on the boundary before reaching the tail flanks and hence to contribute to driving an observed nontrivial magnetospheric convection not controlled by IMF. Such a view is also consistent with observations of Eastman and Hones (1979) showing that the boundary layer has a tendency to become thicker with the distance from the subsolar point.

The magnetospheric boundary is constantly in motion and the satellite crossing the terrestrial magnetospheric boundary observes the magnetopause boundary multiple times; these facts may be interpreted by a wavy motion of the magnetopause boundary passing through the satellite position (e.g., Aubry et al., 1971). It is tempting to suggest further that the satellite is actually passing through the plasma blob formed by the KH instability as is shown in Figure 3.

By using an inhomogeneous model of the magnetospheric boundary it has been demonstrated that a dayside low latitude magnetospheric boundary is a highly dynamic boundary under the presence of the KH instability and a wide velocity boundary layer is formed within the magnetopause current layer by the anomalous viscosity associated with the KH instability.

Acknowledgements. The author would like to thank many physists for their helpful comments, suggestions, and encouragements during the course of this work. Conversations with J. Berchem and R.C. Elphic on magnetometer observations of the ISEE magnetopause crossings were helpful. This work was supported by Japan Ministry of Education grant 59740203.

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(Received June 10, 1985;
accepted July 4, 1985.)