Evolution of Kelvin-Helmholtz instability at Venus in the presence of the parallel magnetic field

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Abstract

Two-dimensional MHD simulation was performed to study the evolution of Kelvin-Helmholtz (KH) instability on Venusian ionopause in response to the strong sheared velocity flow in presence of the in-plane magnetic field parallel to the direction of the flow. The Key result from our simulations is that both of the density increase and the parallel magnetic component on the boundary layer play a role of stabilizing the instability. In the high density ratio cases, the value of final total magnetic energy in the quasi-steady status is much more than that of the initial status, which is quite distinct from that with low density increase. The nonlinear development of case with high density increase and uniform magnetic field is of interest that a single magnetic island forms before the instability saturation. In the non-linear development phase, a new magnetic island arises associated with magnetic reconnection occurring inside the narrow high rolled up density region, combining the pre-existing magnetic island together to form a quasi-steady two island pattern.

1. Introduction

Direct interaction between solar wind and Venusian ionosphere gives rise to dayside bow shock constraining magnetosheath with Venusian ionopause. In addition, a region of enhanced magnetic field, referred to magnetic mental or magnetic barrier [1-3], exists outward of Venusian ionopause. Accordingly, different types of boundary layers involving ionopause and induced magnetopause inside magnetic sheath at Venus exist. Due to strong flow shearing on these boundary layers, the subsequent Kelvin-Helmholtz (KH) instability is considered a principal mechanism for formation of plasma waves and detachment of plasma clouds around Venus.

This hypothesis has been proven by abundant observations and numerical simulations. PVO observations revealed a wavy structure of the dayside ionopause [3]. PVO and VEX observations indicates global vortices associated with KH instability downstream of the Venusian bow shock accelerate heavy ionospheric ions such as oxygen, leading to their escape [4].. In conjunction with ideal MHD simulations, Amerstorfer et al. [5] and Zellinger [6] recently suggested that the density jump on boundary layers around Venus has proportional effect on the growth rate of KH instability. However, the magnetic field model taken by Amerstorfer et al. [5] and Zellinger et al. [6] is only the component perpendicular to the direction of sheared velocity on the boundary layer. It is quite inconsistent with the results from observation and global simulations that the magnetic component parallel to the direction of velocity is considerable [7]. From a theoretical point of view, the in-plane magnetic component parallel to the direction of the flow tends to suppress the growth of the KH vortex [8]. This paper will study the behavior of the KH vortex in the presence of the parallel magnetic field under actual situations of solar wind interaction with Venus.

2. MHD equations and numerical algorithm

We adopt the second-order TVD scheme to solve the ideal eight-wave MHD equations. We distinguish between the following two cases: (i) a uniform case with constant parallel magnetic field; (ii) a one-side case with constant parallel magnetic field on one side and null on another. Hereafter we define a control parameter $\alpha = \boldsymbol{B}_1/\boldsymbol{B}_0$ as the ratio of

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in-plane magnetic field, adapted from Ref. [9]. Therefore, the uniform case is corresponding to α=1, the one-side case α=0.

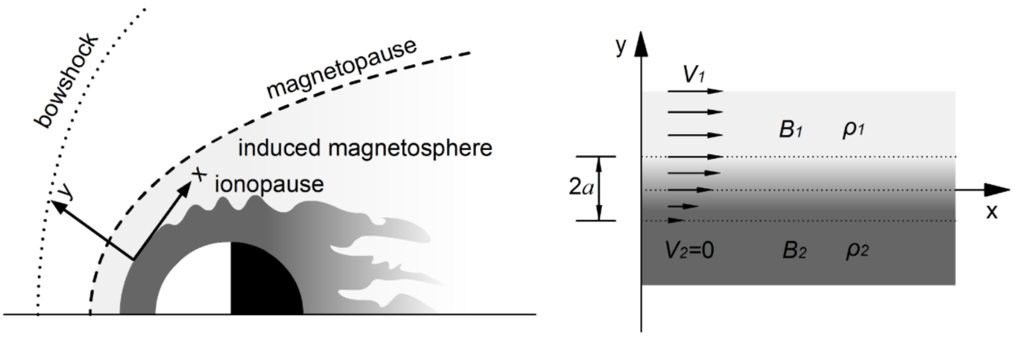


Figure 1 Sketch of the local coordinate system in the *xy*- plane. *a* denotes the half thickness of the initial shear.

For the present study, the values for the initial magnetic field and plasma properties on the two sides of Venusian ionosphere are chosen according to the observations of PVO and Venus VEX [2, 7, 10] which are summarized in Table 1 and Table 2.

Table 1 the values for the normalization

Quantity	Unit
Magnetic field B_1	20 nT
Number density n_1	20 cm^{-3}
Length scale L_1	600 km
Velocity V_{A1}	98.2 $km \cdot s^{-1}$

Table 2 initial magnetic field and plasma properties

Location	***B***, nT	*V*, $km \cdot s^{-1}$	*n*, cm^{-3}
Upper side	10～20	100～200	20
Lower side	20～0	0	>20

3 Numerical Results

In order to guarantee the occurrence of the instability [11], the amplitudes of the velocity shear and magnetic field shear are determined by the criteria in the case of absence of density jump. Introducing the ratio of density $\kappa=\rho_1/\rho_2$ between the two sides of the layer, this condition can be expressed as the relation associated with the initial Alfven Mach number of the upper side

$$M_{A1} > \sqrt{\frac{1+\kappa}{\kappa}\left(1+\alpha^2\right)}$$

According to Table 2, the range of M_{A1} is 1～4. In order to study the correlations of density increase and the in-plane magnetic component parallel to the direction of flow with the development of KH instability, we choose M_{A1}=4 to guarantee the occurrence of highly rolled-up vortex in response to the different density increase on the boundary layer.

We take the logarithm of the *y* component of the total kinetic energy $E_y^*=\iint(0.5\rho V_y^2)dxdy$ of each time step to get the linear growth rate from a slope of linear function fitted to the growth phase. The saturation level E_{max} is determined as the first maximum value in $E_y(t)$, which is reached at time t_{max}. Figure 2(A) indicates the sheared magnetic field acts to destabilize the instability. Figure 2(B) demonstrates the time history of the total magnetic energy, $E_{mag}=\iint((B_x^2+B_y^2)/2E_{mag0})dxdy$, where E_{mag0} is the initial total magnetic energy. It indicates that E_{mag} increases in the initial phase of the instability until E_y reaches E_{max} at t=t_{max}, where the Maxwell stresses and the pressure gradient achieves a close balance almost everywhere. Due to the less stabilizing effect of the magnetic field in one-side case, E_y reaches higher value than that of the uniform magnetic field case. After E_y saturates, the Maxwell stresses exceed the pressure gradient, leading to stabilizing the instability in the non-linear phase.

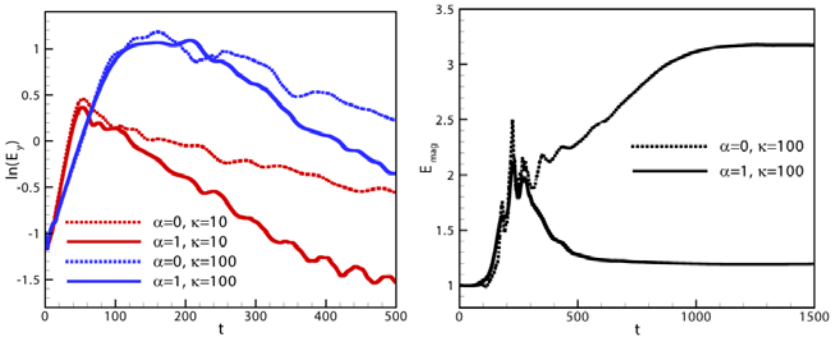
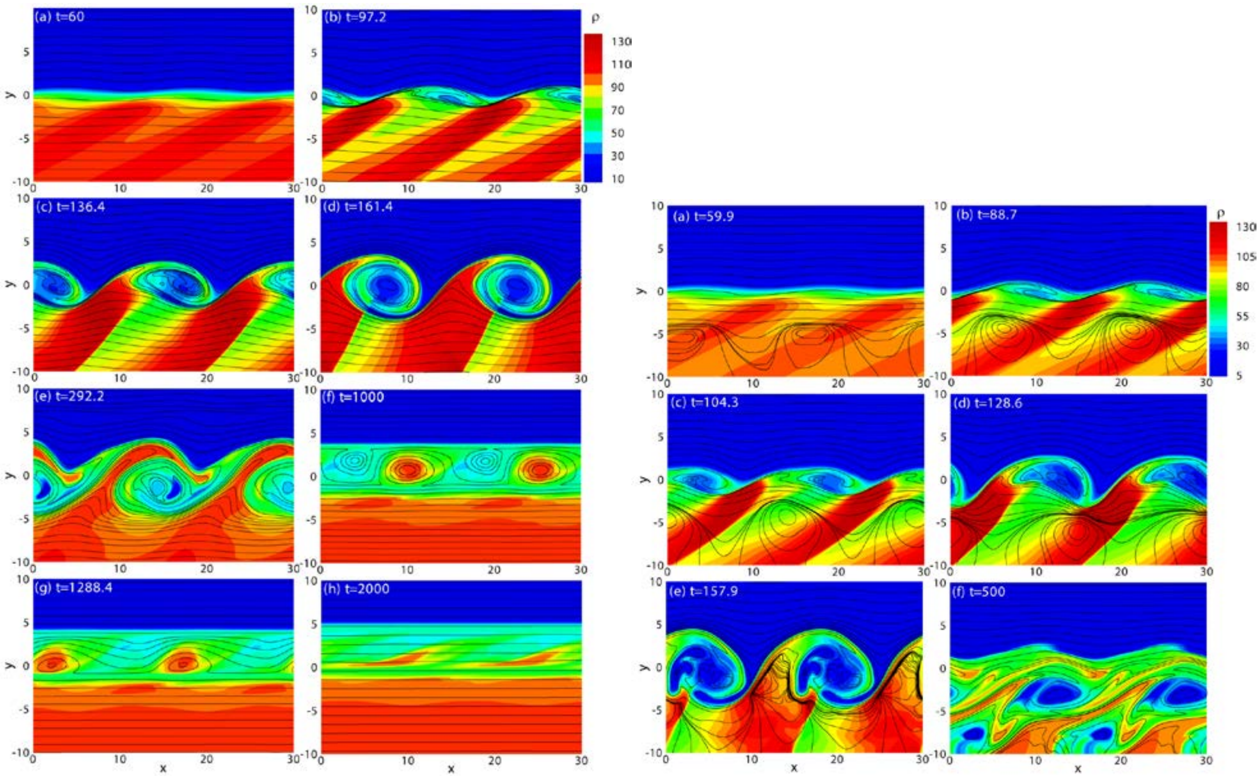


Figure 2 Temporal variation of energy

Figure 3(A – B) display the temporal results for cases of α=1 & κ=100, α=0 & κ=100 respectively. There are clear discrepancies of nonlinear developments of the instabilities of high and low density increase on the boundary layer. Though small magnetic eddies come into being before saturation, vortex coalescence would lead to merging these small structures. As a consequence, a single magnetic island forms inside the strongly sheared region at the end of the linear phase. Then because of joint contribution from magnetic tension and pressure gradient, the single island pattern is deformed. A new magnetic island arises and combines the pre-existing magnetic island together to form a quasi-steady two island pattern. This pattern subsequently persists for a long period until the two magnetic islands die away because of the strong magnetic tension, instead of a steady pattern with almost uniform magnetic field.



(A) (B)

Figure 7 Evolution of density contours and magnetic field lines, (A) is for case of α=1 & κ=100 and (B) α=0 & κ=100

The history of total magnetic energy in the nonlinear phase for case of κ=100, α=0 is similar to the case of low density increase κ=100, α=0, but nevertheless the value of the final total magnetic energy is almost 20% higher than the initial one, as shown in Figure 2(B). Moreover, the tendency of variation of total magnetic energy in the nonlinear phase for case of κ=100, α=1 is opposite to those of other cases. Though oscillations at the beginning of the nonlinear phase, the total magnetic energy keeps increasing until a quasi-steady status sets in. The value of final total magnetic energy is more than three times than that of the initial status. From the viewpoint of energy conservation, magnetic energy is transferred from kinetic energy and high inertial energy of plasma associated with high density increase.

4 Summary and Conclusion

The interplanetary magnetic field is supposed to be perpendicular to the flow of the solar wind when KH instability occurs at the terminator ionopause of Venus. Under the actual conditions from observations, we choose MA1=4 to guarantee the occurrence of highly rolled-up vortex in response to the different density increase on the boundary layer, which corresponds to the low parallel magnetic field. Our numerical results demonstrate that a decrease of the density ratio yields a decrease of the growth rate of the instability, which illustrating the destabilizing effects of the density ratio. In addition, numerical results clearly indicate the stabilizing effect of the uniform magnetic field, accounting for the lower growth rate than that of the sheared magnetic field case. Moreover, the saturation level is always lower in the uniform magnetic field case. In the nonlinear phase, the stabilizing effect of the uniform magnetic field persists. As a consequence, y component of the total kinetic energy decreases rapidly.

In the case of high density increase with uniform magnetic field on the boundary, small magnetic eddies come into being before saturation, vortex coalescence would lead to merging these small structures. As a consequence, a single magnetic island forms inside the strongly sheared region at the end of the linear phase. Then because of joint contribution from magnetic tension and pressure gradient, the single island pattern is deformed. Due to the subsequent magnetic reconnection occurring inside the narrow high density region, a new magnetic island arises and combines the pre-existing magnetic island together to form a quasi-steady two island pattern. This pattern subsequently persists for a long period until the two magnetic islands die away because of the strong magnetic tension, instead of a steady pattern with almost uniform magnetic field.

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