Heating of the background plasma by obliquely propagating Alfven waves excited in the electromagnetic alpha/proton instability

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Previous studies have shown that obliquely propagating Alfven waves may be excited in the electromagnetic alpha/proton instability. In this paper, two-dimensional hybrid simulations are performed to investigate the nonlinear evolution of the electromagnetic alpha/proton instability. We further find that the obliquely propagating Alfven waves excited by the alpha/proton instability have nearly linear polarization. The background proton component, as well as the alpha component, can be resonantly heated by the oblique Alfven waves. The implications of our results to the unsolved solar coronal hearing problem are also discussed in this paper. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3693373]

I. INTRODUCTION

Counter-streaming ions are a very common occurrence in space plasmas.1–4 They can lead to a number of plasma instabilities and enhanced field fluctuations.5–8 Among these, electromagnetic ion/ion instabilities have attracted much interest due to many relevant applications in space physics research, such as the study of the Earth’s magnetotail,9,10 bow shock,11,12 and solar wind.13,14 Not only can ion beam instability explain many commonly observed wave activities, they can also lead to energy and momentum transfer.

The characteristics of the excited waves by the electromagnetic ion/ion instability have been studied thoroughly.5–8 Both linear Vlasov theory and hybrid simulations have shown that the electromagnetic ion/ion instabilities can excite both parallel propagating magnetosonic waves and obliquely propagating Alfven waves.5,6,8 When the relative drift speed between the beam component and the background component is large compared to the Alfven speed, the right hand magnetosonic mode is the most unstable. However, when the relative streaming speed is a little bit larger than the Alfven speed, the oblique Alfven modes may have competitive growth rates.15 In relatively low beta plasma, the oblique Alfven instability has lower threshold, while the magnetosonic instability has lower threshold in higher beta plasma.15–19 The temperature anisotropy of either the background component or beam component is also found to have effects on the electromagnetic ion/ion instabilities, which will lead to a reduction in both the growth rate and the amplitude of the magnetosonic and Alfven waves.13,20 With two-dimensional (2D) hybrid simulations, Lu et al.5 further found that during the evolution of the alpha/proton instability in low beta plasma, both the wave numbers and frequencies of the Alfven waves drift to smaller values, and the propagation angles (the angle between the wave number and the background magnetic field) decrease.

In this paper, with 2D hybrid simulation we investigate the heating of the background protons by the oblique Alfven waves excited by the electromagnetic alpha/proton instability in low beta plasma, which has not been studied in previous researches.

The organization of this article is as follows. The simulation model is described in Sec. II. The simulation results are illustrated in Sec. III, and a summary and discussion are given in Sec. IV.

II. SIMULATION MODEL

In the paper, a 2D hybrid simulation model with periodic boundary condition is used to study the electromagnetic alpha/proton instability. In the model, the ions are treated kinetically with the standard particle-in-cell method, while the electrons are treated as massless fluid. The particles are advanced according to the well-known Boris algorithm, while the electromagnetic fields are calculated with an implicit algorithm.5,21 In the model, the units of space and time are \( c/\omega_{pp} \) (where \( c/\omega_{pp} \) is the proton inertial length, \( c \) is the speed of light, \( \omega_{pp} \) is the proton plasma frequency based on total number density \( n_0 = n_p + n_e \), \( n_p \) and \( n_e \) are the densities of the proton and alpha components, respectively) and \( \Omega_p^{-1} \) (where \( \Omega_p = c B_0/|m_p c| \) is the proton gyro-frequency, and \( B_0 \) is the background magnetic field), respectively. The number of grid cells is \( n_x \times n_y = 512 \times 256 \), and the grid cell size is \( \Delta x = \Delta y = 0.8 c/\omega_{pp} \). Initially, both alpha particles and protons satisfy isotropic Maxwellian velocity distribution, and they have the same thermal speed. One hundred particles of each component are uniformly distributed in each cell. The relative streaming velocity between the alpha and proton components is parallel to the background magnetic field, which is \( \mathbf{B}_0 = B_0 \hat{x} \). In our model, we choose \( n_x/n_e = 0.05 \) (where \( n_e = n_p + 2n_s \) is the electron number density), and the initial relative drift speed between protons and alpha particles is set to 1.55\( V_A \) (\( V_A \) is the Alfven speed). The time step is \( \Omega_p \Delta t = 0.025 \).

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Alfven waves are excited. In this case, only obliquely propagating Alfven waves are excited. The simulations are performed in the center-of-mass frame, where the charge neutrality \( \sum j_n j = 0 \), where \( j \) denotes the species of particles) and the zero current condition \( \sum j_n V_{0j} = 0 \) are satisfied initially. In order to suppress the magnetosonic instability, we set \( b_p = 0.01 \) (the proton plasma beta). In this case, only obliquely propagating Alfven waves are excited.

### III. SIMULATION RESULTS

In the simulation, only obliquely propagating Alfven waves are excited. Fig. 1 shows the time evolution of (a) the amplitude of the fluctuating magnetic field \( \delta B^2/\delta B_0^2 \), (b) the relative drift speed between protons and alpha particles \( U_{\alpha p}/V_A \).

Simultaneously, with the excitation of the Alfven waves, the relative drift speed between the proton component and alpha component \( U_{\alpha p} \) decreases gradually until to about one local Alfven speed.

Now let us discuss the detailed characteristics of the excited Alfven waves by the electromagnetic alpha/proton instability. Figure 2 shows the characteristics of \( k_x - k_y \) diagram obtained from the fast Fourier transform (FFT) transforming of \( B_x/B_0 \) at (a) \( \Omega_p t = 105 \), (b) \( \Omega_p t = 250 \), and (c) \( \Omega_p t = 700 \). The propagating angle \( \theta = \arctan(k_y/k_x) \) has a definite range, and it becomes smaller during the nonlinear evolution. Meanwhile, the wave number of the dominant mode, which has the maximum amplitude of fluctuating magnetic field, also decreases during the evolution. Figure 3 describes the spectrum evolution of the wave frequencies, which is obtained with the following method: we first calculate wavelet power spectrum of the time series of \( B_x/B_0 \) at \( \Omega_p t = 250 \) and \( \Omega_p t = 700 \). Similar results have been obtained in Ref. 8. Figure 4 illustrates the time evolution of amplitude of the fluctuating magnetic field \( \delta B_{x,y}^2/B_0^2 \) (where \( \delta B_{x,y}^2 = \delta B_x^2 + \delta B_y^2 \) and \( \delta B_z^2/B_0^2 \). We can find that the amplitude of \( \delta B_y^2/B_0^2 \) is much larger than that of \( \delta B_x^2/B_0^2 \). Therefore, the excited Alfven waves have nearly linear polarization, and both the frequencies and wave numbers decrease during the nonlinear evolution.

Figure 5 shows the time evolution of (a) the parallel temperature \( T_{\parallel p}/T_{\parallel 0} \) (\( T_{\parallel 0} \) is the initial parallel temperature of the alpha component) and perpendicular temperature \( T_{\perp x}, T_{\perp 0} \) (\( T_{\perp 0} \) is the initial perpendicular temperature of the alpha component) of alpha particles and (b) illustrates the parallel temperature \( T_{\parallel p}/T_{\parallel 0} \) and the perpendicular temperature \( T_{\perp p}/T_{\perp 0} \) (\( T_{\perp 0} \) is the initial parallel temperature of protons) and perpendicular temperature \( T_{\perp p}/T_{\perp 0} \) (\( T_{\perp 0} \) is the initial parallel temperature of the proton component) of the proton component. The parallel and perpendicular temperatures are calculated using the following procedure: we first calculate the parallel temperature \( T_{\parallel 0} = (m_j/k_B)((v_{xj} - \langle v_{xj} \rangle)^2 \) and the perpendicular temperature \( T_{\perp 0} = (m_j/2k_B)((v_{yj} - \langle v_{yj} \rangle)^2 + (v_{zj} - \langle v_{zj} \rangle)^2 \) in every grid cell (the bracket \( \langle \cdot \rangle \) denotes an average over one grid cell.)

\[ T_{\parallel 0} = (m_j/k_B)((v_{xj} - \langle v_{xj} \rangle)^2 \]
\[ T_{\perp 0} = (m_j/2k_B)((v_{yj} - \langle v_{yj} \rangle)^2 + (v_{zj} - \langle v_{zj} \rangle)^2 \]

\[ T_{\parallel p}/T_{\parallel 0} \]
\[ T_{\perp p}/T_{\perp 0} \]
cell), and then, the temperatures are averaged over all grids. Using this method, the effects of the bulk velocity at each location on the thermal temperature can be eliminated.8,21,22 From the figure, we can find that with the excitation of the obliquely propagating Alfven waves both the alpha and proton components can be heated. At the same time, both of them are first heated in the perpendicular direction and then in the parallel direction. At the quasi-equilibrium stage, the parallel temperature $T_{[x]}/T_{[a]}$ and perpendicular temperature $T_{[z]}/T_{[a]}$ of the alpha component are 25 and 24, respectively, while the parallel temperature $T_{[p]}/T_{[0]}$ and perpendicular temperature $T_{[z]}/T_{[0]}$ of the proton component are 2.1 and 3.5. Therefore, the temperature anisotropy of the proton components can be heated. At the same time, both of them are first heated in the perpendicular direction and then in the parallel direction. In this way, at the quasi-equilibrium stage, a shell-like distribution is formed. For alpha particles, they are first scattered in the perpendicular direction and then in the parallel direction. In this way, at the quasi-equilibrium stage, a shell-like distribution is formed. For protons, the scattering occurs mainly in the perpendicular direction, and an anisotropic distribution is formed at last.

FIG. 3. (Color online) The contour of the spectrum evolution of the wave frequencies obtained from the average value of the wavelet power spectrum of the time series of $B_z/B_0$ at 100 selected grids.

The heating of alpha particles and protons can be explained by the resonant interactions between particles and the obliquely propagating Alfven waves excited in the alpha/proton instability. The resonant interactions can be quantitatively illustrated by the cyclotron resonant factor,5–7,14,23 which is

$$\varepsilon_j^\pm = \omega - k_j|U_j| \pm \Omega_j \pm \frac{|\Omega_j|}{k_j|v_{jth}|},$$

where $\omega$ is the wave frequency, $k_j$ is the parallel wave number, $U_j$ and $\Omega_j = q_jB_0/m$ are the bulk velocity, gyro-frequency, and the parallel thermal velocity of the $j$ th species. Small or intermediate values of the factor ($|\varepsilon| < 3$) correspond to a resonant interaction between the wave and particles.5–7,14,23

We can calculate the cyclotron resonant factors of alpha particles and protons based on the frequencies (Fig. 2) and wave numbers (Fig. 3) of the oblique Alfven waves and the other parameters. For the domain mode and alpha particles, when the waves begin to be excited ($\Omega_j = 70$), the cyclotron resonant factor is about 11.5 for the left-hand waves, and it is about 0.4 for the right-hand waves. For the domain mode and protons, the cyclotron resonant factor is about 2.0 for the left-hand waves, and it is about 21.5 for the right-hand waves. The excited obliquely propagating Alfven waves are nearly linearly polarized, which can be considered to be superimposed by left- and right-hand polarized Alfven waves. Therefore, the waves can resonantly interact with

FIG. 4. The time evolution of amplitude of the fluctuating magnetic field $\delta B_{[x]}/B_0$ (where $\delta B_{[x]} = \delta B_x^0 + \delta B_z^0$) and $\delta B_{[z]}/B_0$. 

FIG. 5. The time evolution of (a) the parallel temperature $T_{[x]}/T_{[a]}$ and perpendicular temperature $T_{[z]}/T_{[a]}$ of the alpha component, (b) the parallel temperature $T_{[p]}/T_{[0]}$ and perpendicular temperature $T_{[z]}/T_{[0]}$ of the proton component. Dashed lines represent the parallel temperatures, and solid lines represent the perpendicular temperatures.
FIG. 6. The scatter plots of alpha particles in the ($v_{\parallel}, v_{\perp}$) space at different times.

FIG. 7. The scatter plots of protons in the ($v_{\parallel}, v_{\perp}$) space at different times.
both alpha particles and protons, and they can heat the background protons, as well as alpha particles.

IV. DISCUSSION AND CONCLUSIONS

A 2D hybrid simulation is employed to study the electromagnetic alpha/proton instability in low beta plasma. The obliquely propagating Alfvén waves with a nearly linear polarization are excited. The background protons, as well as the beam alpha particles, can be resonantly heated by the Alfvén waves. Although the heating of the alpha component in the alpha/proton instability has been investigated in the previous researches, we further find that the background protons can also be heated in the alpha/proton instability in low beta plasma. The heating of the background protons is more efficient in the perpendicular direction. One thing we should emphasize is that the mechanism of the heating is different from that during the ion pickup process by the intrinsic Alfvén waves. In that situation, the heating is due to the phase difference randomization between pickup ions. Here, the background protons can only be heated by the obliquely propagating Alfvén waves with the linear polarization. When the plasma beta becomes larger, the oblique Alfvén waves weaken and the parallel magnetosonic waves strengthen, the heating of the background plasma also becomes weaker and weaker until disappears.

In the solar corona, bursty heating events happen frequently. Magnetic reconnection is considered as a highly efficient engine to convert magnetic energy into plasma kinetic and thermal energies. Drake et al. proposed that in magnetic reconnection the ions crossing the narrow boundary into the exhaust can be heated like the pickup ions. Liu et al. found that the ions can also be heated by the slow shocks formed in magnetic reconnection.

An ion beam can be formed in the outflow region of magnetic reconnection and in the upstream of the slow shock. The ion beam may excite oblique Alfvén waves by such a beam due to the ion/ion instabilities. Therefore, the heating mechanism of the background plasma proposed in the paper provides another possibility of ion heating related with magnetic reconnection and may have relevance with bursty heating events in solar corona.

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