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PHYSICS OF PLASMAS **19**, 032901 (2012)

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.*[8] 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.[8,21] In the model, the units of space and time are c/ω_{pp} (where c/ω_{pp} is the proton inertial length, c is the speed of light, ω_{pp} is the proton plasma frequency based on total number density $n_0 = n_p + n_\alpha$. n_p and n_α are the densities of the proton and alpha components, respectively) and Ω_p^{-1} (where $\Omega_p = eB_0/m_p c$ 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 $\mathbf{B}_0 = B_0\hat{\mathbf{x}}$. In our model, we choose $n_\alpha/n_e = 0.05$ (where $n_e = n_p + 2n_\alpha$ is the electron number density), and the initial relative drift speed between protons and alpha particles is set to $1.55V_A$ (V_A is the Alfven speed). The time step is $\Omega_p\Delta t = 0.025$.

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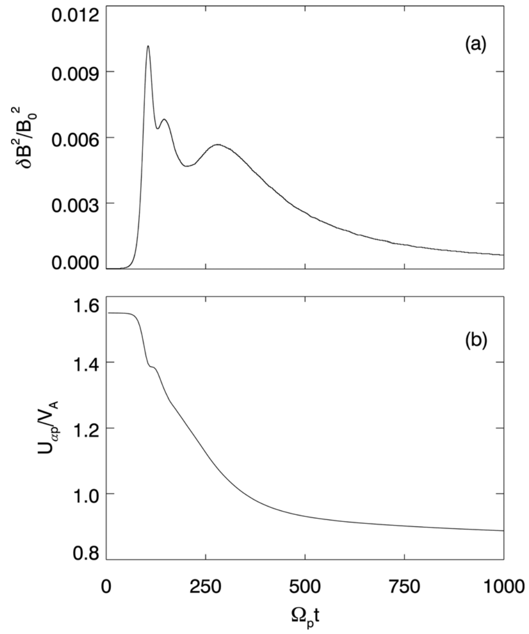

FIG. 1. The time evolution of (a) the amplitude of the fluctuating magnetic field $\delta B^2/\delta B_0^2$, (b) the relative drift speed between protons and alpha particles $U_{\alpha p}/V_A$.

The simulations are performed in the center-of-mass frame, where the charge neutrality ($\sum_j e_j n_j = 0$, where j denotes the species of particles) and the zero current condition ($\sum_j e_j n_j V_{0j} = 0$) are satisfied initially. In order to suppress the magnetosonic instability, we set $\beta_p = 0.01$ (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 the proton component and alpha component $U_{\alpha p}/V_A$. The Alfven waves begin to be excited at $\Omega_p t \approx 60$ and saturate at $\Omega_p t \approx 105$ with the amplitude $\delta B^2/\delta B_0^2 \approx 0.010$. Then, the wave amplitude begins to decrease gradually until to the quasi-equilibrium stage (from $\Omega_p t \approx 700$) with the amplitude about $\delta B^2/\delta B_0^2 \approx 0.001$. 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_z/B_0 at (a) $\Omega_p t = 105$, (b) $\Omega_p t = 250$, and (c) $\Omega_p t = 700$, respectively. 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.[8] 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_z/B_0 at 100 selected grids, and the spectrum evolution shown in Fig. 3 is the average value of these grids. The wave frequencies decrease during the nonlinear evolution, and the frequency of the domain mode drifts from $\omega = 0.7\Omega_p$ at $\Omega_p t = 100$ to $\omega = 0.5\Omega_p$ at $\Omega_p t = 500$. 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 $\delta B_z^2/B_0^2$ is much larger than that of $\delta B_{x,y}^2/B_0^2$. 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 $T_{\parallel\alpha}/T_{\parallel\alpha 0}$ ($T_{\parallel\alpha 0}$ is the initial parallel temperature of the alpha component) and perpendicular temperature $T_{\perp\alpha}/T_{\perp\alpha 0}$ ($T_{\perp\alpha 0}$ is the initial perpendicular temperature of the alpha component) of alpha particles and (b) illustrates the parallel temperature $T_{\parallel p}/T_{\parallel p0}$ ($T_{\parallel p0}$ is the initial parallel temperature of protons) and perpendicular temperature $T_{\perp p}/T_{\perp p0}$ ($T_{\perp p0}$ 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 $T_{\parallel j} = (m_j/k_B)\langle (v_x - \langle v_x \rangle)^2 \rangle$ and the perpendicular temperature $T_{\perp j} = (m_j/2k_B)\langle (v_y - \langle v_y \rangle)^2 + (v_z - \langle v_z \rangle)^2 \rangle$ in every grid cell (the bracket $\langle \bullet \rangle$ denotes an average over one grid

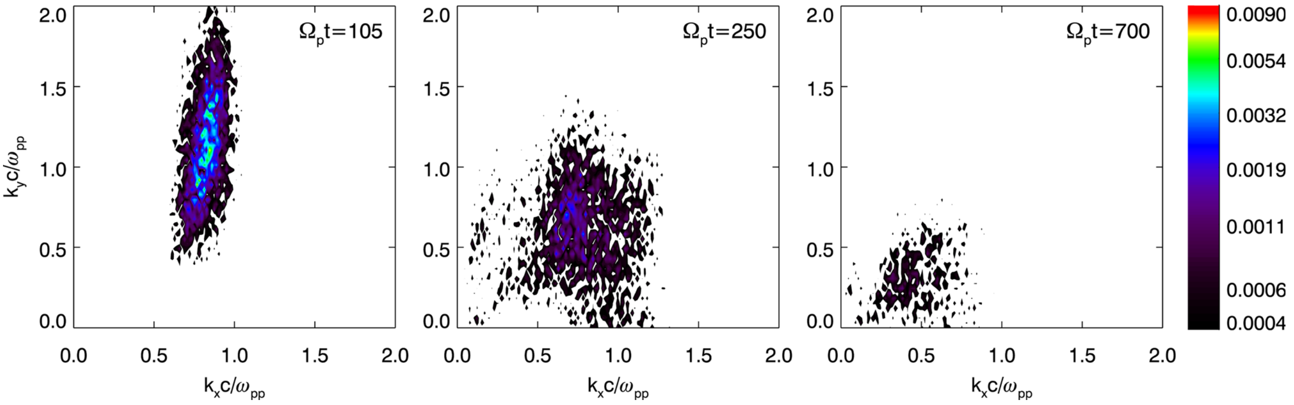

FIG. 2. (Color online) The contour of the characteristics of $k_x - k_y$ diagram obtained from the FFT transforming of B_z/B_0 at $\Omega_p t = 105$, $\Omega_p t = 250$, and $\Omega_p t = 700$.

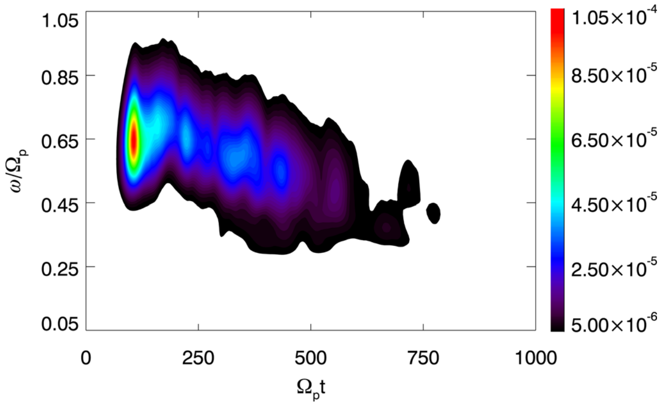

FIG. 3. (Color online) The contour of the spectrum evolution of the wave frequencies obtained from the average value of the wavelet power spectrum of the time series of B_z/B_0 at 100 selected grids.

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 $T_{\parallel\alpha}/T_{\parallel\alpha0}$ and perpendicular temperature $T_{\perp\alpha}/T_{\perp\alpha0}$ of the alpha component are 25 and 24, respectively, while the parallel temperature $T_{\parallel p}/T_{\parallel p0}$ and perpendicular temperature $T_{\perp p}/T_{\perp p0}$ of the proton component are 2.1 and 3.5. Therefore, the temperature anisotropy of the proton component is about $T_{\perp p}/T_{\parallel p} \approx 1.7$. The heating of the alpha and proton components can be illustrated more intuitively by Figs. 6 and 7, which show the scatter plots of alpha particles and protons at different time, respectively. In the figures, the particles in 25 cells are recorded, and in every cell, the bulk velocity has been subtracted in order to eliminate the contribution of the bulk velocity.[8] 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.

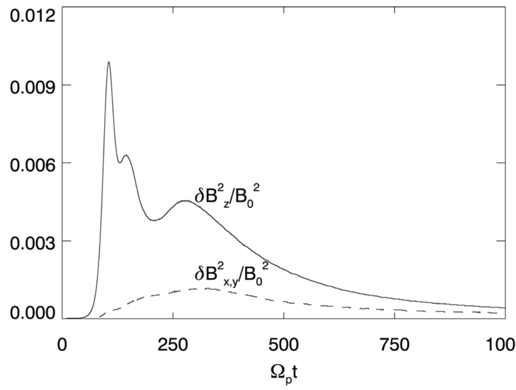

FIG. 4. The time evolution of amplitude of the fluctuating magnetic field $\delta B_{x,y}^2/B_0^2$ (where $\delta B_{x,y}^2 = \delta B_x^2 + \delta B_y^2$) and $\delta B_z^2/B_0^2$.

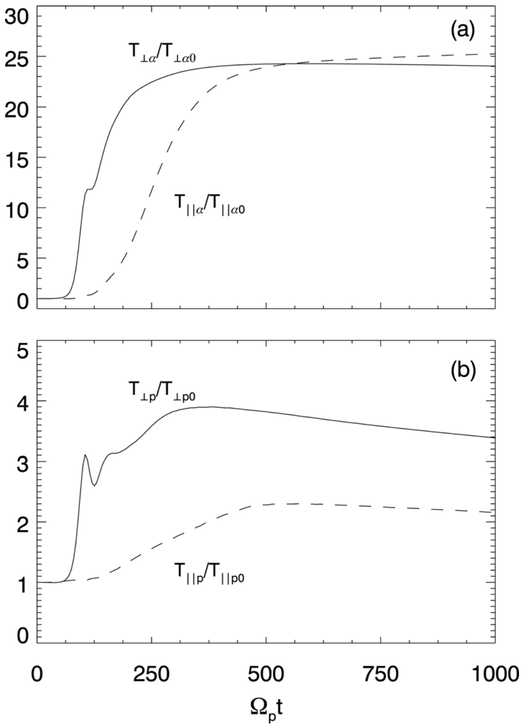

FIG. 5. The time evolution of (a) the parallel temperature $T_{\parallel\alpha}/T_{\parallel\alpha0}$ and perpendicular temperature $T_{\perp\alpha}/T_{\perp\alpha0}$ of the alpha component, (b) the parallel temperature $T_{\parallel p}/T_{\parallel p0}$ and perpendicular temperature $T_{\perp p}/T_{\perp p0}$ of the proton component. Dashed lines represent the parallel temperatures, and solid lines represent the perpendicular temperatures.

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

$$\zeta_j^{\pm} = \frac{\omega - k_\parallel U_j \pm \Omega_j}{k_\parallel v_{\parallel j\mathrm{th}}}, \tag{1}$$

where ω is the wave frequency, $k_\parallel$ is the parallel wave number. $+$ and $-$ represent the right- and left-hand polarized waves, respectively. U_j, $\Omega_j = q_j B_0/mc$ and $v_{\parallel j\mathrm{th}} = \sqrt{2k_B T_{j\parallel}/m_j}$ are the bulk velocity, gyro-frequency, and the parallel thermal velocity of the j th species. Small or intermediate values of the factor ($|\varsigma| < 3$) 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 ($\Omega_p t = 70$), the cyclotron resonant factor is about 11.5 for the left-hand waves, and it is about 0.24 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

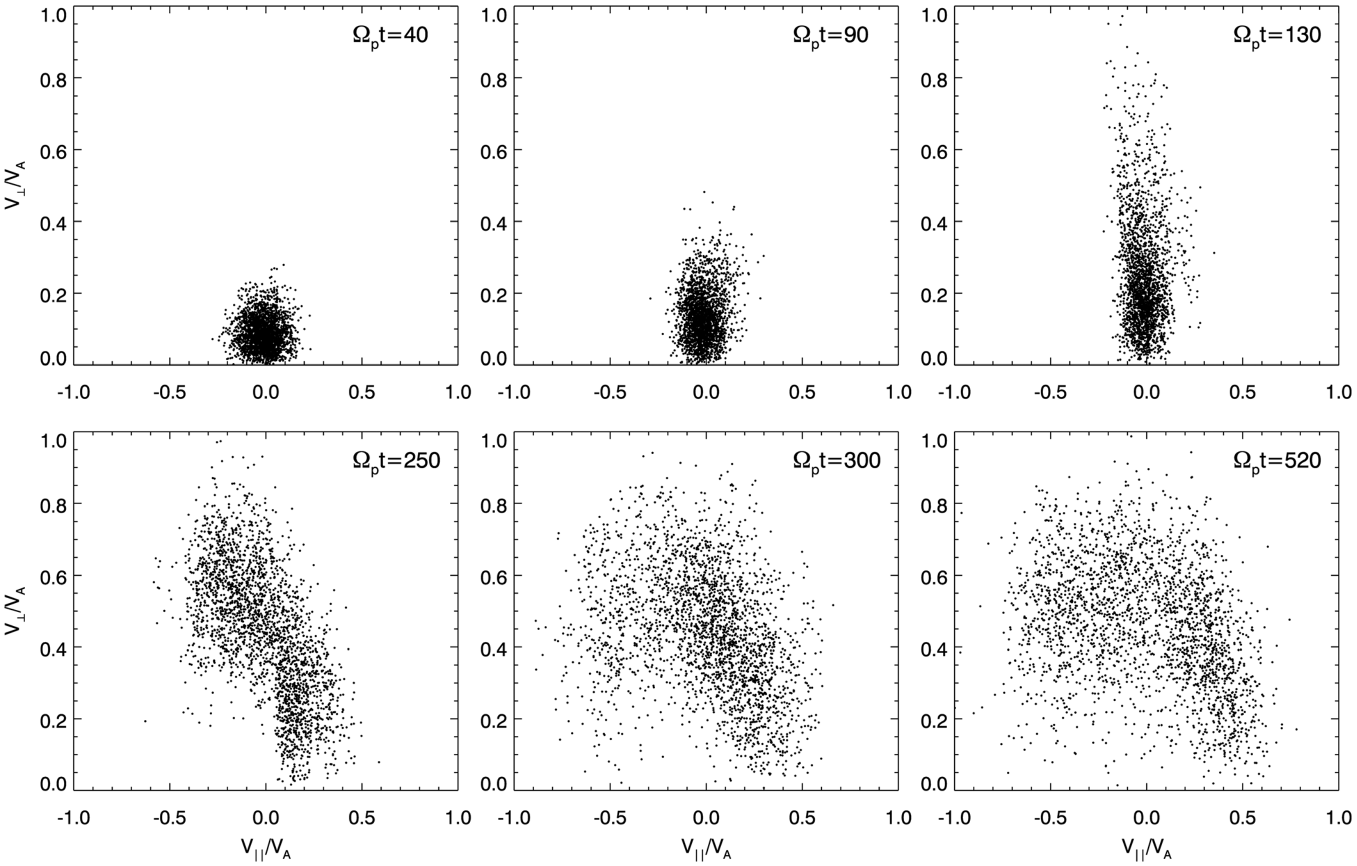

FIG. 6. The scatter plots of alpha particles in the ($v_\parallel$, $v_\perp$) at different times.

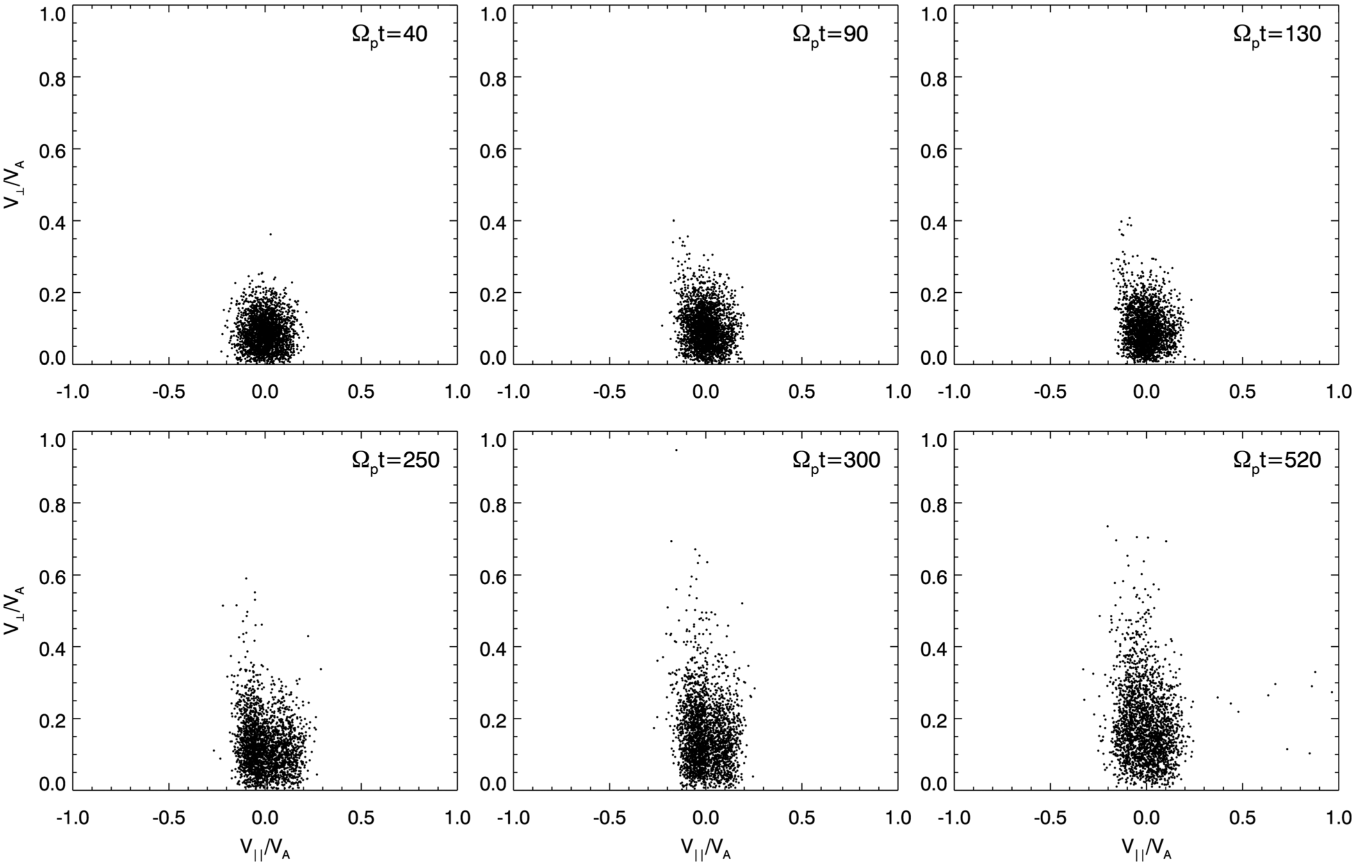

FIG. 7. The scatter plots of protons in the ($v_\parallel$, $v_\perp$) space at different times.

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 Alfven waves with a nearly linear polarization are excited. The background protons, as well as the beam alpha particles, can be resonantly heated by the Alfven waves. Although the heating of the alpha component in the alpha/proton instability has been investigated in the previous researches,[5–8,14] we further find that the background protons can also been 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 Alfven waves.[24,25] 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 Alfven waves with the linear polarization. When the plasma beta becomes larger, the oblique Alfven 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.[26,27] It is commonly believed that the energy source of the bursty heating events is magnetic reconnection.[28–30] Magnetic reconnection is considered as a highly efficient engine to convert magnetic energy into plasma kinetic and thermal energies. Drake *et al.*[31] proposed that in magnetic reconnection the ions crossing the narrow boundary into the exhaust can be heated like the pickup ions. Liu *et al.*[32] found that the ions can also been heated by the slow shocks formed in magnetic reconnection.

An ion beam can be formed in the outflow region of magnetic reconnection[26,27] and in the upstream of the slow shock.[32] The ion beam may excite oblique Alfven 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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