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Contributions to Plasma Physics

Heating and acceleration of ions with Kappa distribution functions by low-frequency Alfvén wave

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Abstract

Heating and acceleration of ions with Kappa distribution functions (with parameter κ) in low-beta plasmas, by a low-frequency Alfvén wave, is investigated using test-particle simulations, yielding interesting new results. As long as the Alfvén wave amplitude is sufficiently large, the computed net heating energy of ions becomes independent of the wave frequency and amplitude, always approaching the same value of $mv_A^2/2$. The eventual energy of ions is dictated only by the initial ion energy and the ratio of the magnetic field energy density to the plasma density. The heating effect of the Kappa ions increases with κ. During the heating process, the ions are picked up by the Alfvén wave and pitch angle scattered, forming a quasi-isotropic spherical shell velocity distribution. The Kappa ions are accelerated in the parallel direction, reaching a bulk flow speed roughly equal to the local Alfvén speed. Higher κ-value in the initial Kappa distribution leads to faster saturation. The above results may explain certain features of the ion heating and acceleration in the solar wind and corona.

KEYWORDS

Alfvén wave, corona, non-resonance interaction, wave heating

1 | INTRODUCTION

For a long time, both the coronal heating and the solar wind acceleration problems are the major topics in plasma physics and plasma astrophysics.[1–6] This question is very important in space environment's research. It is generally believed that the interaction between Alfvén waves and particles is a very crucial factor for the heating and acceleration of solar wind and corona. When the Alfvén wave frequency is far less than the ion cyclotron frequency, the cyclotron resonance condition does not occur. In this case, ions can still be heated by Alfvén waves, namely via non-resonant wave-particle interactions.[7–8] Recently, particle heating by low-frequency Alfvén waves have attracted more attention; and most of research shows that the heating is proportional to the amplitude of Alfvén waves.[8–16] Lu et al.[17,18] specifically studied the effects of different polarized Alfvén waves on heating and acceleration in parallel directions along the background magnetic field. In laboratory plasmas, evidences of ion heating by low-frequency Alfvén waves have also been found.[19–22] Stochastic ion heating by obliquely propagating low-frequency Alfvén waves have also been investigated.[23–27] Their studies found that, as long as the Alfvén wave amplitude satisfies a certain threshold condition, the ion non-resonant gyromotion may turn into stochastic motions due to the non-linear coupling. Their research focused on the amplitude threshold that leads to the stochastic heating. However, it is not entirely clear how the ions can get energy in the heating process, and how much energy they can gain from the Alfvén waves. Wang et al.[27] discussed the physical process of heating and acceleration in relation to stochasticity of ions motion. They found that when the wave amplitude exceeds the stochasticity threshold, the asymptotic temperature of ions is independent of the Alfvén wave amplitude but dominated by the Alfvén speed. Dong et al.[28,29] studied the pseudo-heating of ions in the presence of Alfvén waves and proved that this process can be explained by $\mathrm{E} \times \mathrm{B}$ drift. They also investigate minor ion (such as He^{2+}) heating via non-resonant interaction with spectra of linearly and circularly polarized Alfvén waves. Proton perpendicular heating by kinetic Alfvén waves has also been studied systematically by Choi et al.[30,31] More recently, harmonic Alfvén waves in the magnetosphere have been reported by observations,[32] and their interaction with heavy ions have also been simulated.[33]

Up to now, plasmas in thermal equilibrium are the most common model of the wave-particle interaction. However, measurements of plasmas and magnetic fields are very important, if not unique, access to the study of cosmic plasmas. These measurements are obtained by spacecraft in the planetary magnetospheres and Sun-Earth environment. One of the significant findings is that the observed velocity-space distributions have been shown to exhibit a non-thermal equilibrium plasma, which can be described by more general Kappa distribution functions, which in turn are obtained by integrating the suprathermal population into the otherwise Maxwellian distribution.[34–39] There have already been many studies of such velocity distributions in various areas of fundamental and space-plasma physics.[40–44] Using the Kappa distribution has the advantage that the Maxwellian distribution is a special case of the Kappa (κ) function at the $\kappa \to \infty$ limit. The modified solutions were derived from that with the Maxwellian velocity distribution. The modified solutions can represent more general cases. Besides its mathematical generality, like the Maxwellian function, the Kappa velocity distribution is also a special class of solutions to the Vlasov equation.[45–49]

In this paper, based on the simulated time evolution of the velocity distribution and of the temperature of ions with an initial Kappa distribution, we present our study on the heating and acceleration of ions by a parallel propagating low-frequency Alfvén wave, and demonstrate the physical process of ion pickup and pitch angle scattering[50,51] by a low-frequency Alfvén wave, via non-resonant interaction and stochastic heating. Some of the findings are significant and quite different from that of Wang et al.[27]

2 | PHYSICAL MODEL

The standard isotropic, three-dimensional Kappa distribution function can be written as[39]

$$f_\kappa(v) = \frac{N}{\left(\pi\kappa\theta^2\right)^{3/2}} \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)} \left(1 + \frac{v^2}{\kappa\theta^2}\right)^{-(\kappa+1)}, \tag{1}$$

where κ is the spectral index, $\Gamma(x)$ the usual gamma function, and θ a characteristic speed that has been termed an effective thermal speed by some authors. The family of κ ions function may represent very different distributions from the exponential form to the Maxwellian. In particular, the Kappa distribution has the advantage that the Maxwellian distribution is a special case of the Kappa function at the $\kappa \to \infty$ limit, namely

$$f_m(v) = N\left(\frac{1}{\pi v_{\mathrm{th}}^2}\right)^{3/2} e^{-v^2/v_{\mathrm{th}}^2}, \tag{2}$$

where v_{th} is the characteristic (thermal) speed, similar to the θ parameter in the Kappa distribution.

Subsequently, an "equivalent temperature" T of the plasma, is introduced based on the equipartition of energy. We note that this principle is only appropriate for equilibrium distribution, being not rigorously valid for a non-equilibrium distribution. Nevertheless, the "equivalent temperature" is a useful concept that has many practical advantages, and has been widely accepted in practice for non-Maxwellian distributions.[39]

The "equivalent temperature" of ions is calculated, with the Kappa distribution, from the average particle energy, which is mainly specified by the integral of the second statistical moment. This is related to the per particle average energy,

E_κ, by

$$E_\kappa = \frac{1}{2} < mv^2 >= \frac{1}{2N}\int f_\kappa(v) mv^2 d\mathbf{v}. \tag{3}$$

Obviously, the equipartition of energy is strictly applied. The Kappa ions "equivalent temperature," T_κ, can be expressed as

$$T_\kappa = \frac{2}{3k_B}E_\kappa = \frac{< mv^2 >}{3k_B}, \tag{4}$$

where m is the particle mass, k_B the Boltzmann's constant.

In this work, we consider the motion of ions in a thermal non-equilibrium plasma, in the intrinsic presence of an Alfvén wave with $\beta = (\theta/v_A)^2 = 0.01$. Consequently, the test particle simulation is adopted. For simplicity, we assume that the intrinsic Alfvén wave pervades the solar corona and interplanetary space, propagates along a constant background magnetic field $\mathbf{B_0} = B_0\mathbf{i_z}$, and satisfies the dispersion relation $\omega = kv_A$, where ω and k are the wave frequency and wave number, respectively. $v_A = B_0/\sqrt{\mu_0 n_0 m}$ is the Alfvén wave phase speed, n_0 the plasma density.[50,51] The magnetic and electric fields associated with the Alfvén wave, $\delta\mathbf{B}_w$ and $\delta\mathbf{E}_w$, can be written as

$$\delta\mathbf{B}_w = B_k\left(\cos\phi_k\mathbf{i}_x \pm \sin\phi_k\mathbf{i}_y\right), \tag{5}$$

$$\delta\mathbf{E}_w = -v_A\mathbf{i}_z \times \delta\mathbf{B}_w, \tag{6}$$

where $\pm$ corresponds to the right-hand (RH) and the left-hand (LH) polarization of the Alfvén wave, $\mathbf{i}_x$ and $\mathbf{i}_y$ are unit vectors, and $\phi_k = k(v_At - z)$ denotes the wave phase. The particle motion in the Alfvén wave fields is given by

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m}\left[\mathbf{v}\times(\mathbf{B}_0 + \delta\mathbf{B}_w) + \delta\mathbf{E}_w\right], \tag{7}$$

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}. \tag{8}$$

Without loss of generality, in the following test-particle simulation, only the LH polarized Alfvén wave is taken into account. The evolution of the test protons shall be followed. The total magnetic energy of the wave is kept constant. Three values of the wave amplitude will be considered, namely, $B_w^2/B_0^2 = (0.15,\ 0.20,\ 0.25)$. The frequency of the Alfvén wave is $\omega = 0.0375\Omega_0$, much less than the proton cyclotron frequency $\Omega_0 = eB_0/m$. Thus the cyclotron resonance condition is not satisfied. The equations of motion are solved using Boris algorithm, with time step $\Delta t = 0.025\Omega_0^{-1}$[Numerical convergent test with respect to Δt has been performed]. The total number of protons is 162,000 with the Kappa distribution in the velocity space. Periodic boundary conditions are used. The average parallel velocity and the "equivalent temperature" are obtained as follows: first, the average parallel velocity $v_\parallel = \langle v_z\rangle$ and equivalent temperature $T_\kappa = (m/3k_B)\sum_{i=x,y,z}\left\langle(v_i - \langle v_i\rangle)^2\right\rangle$ are computed in each grid cell (where the angular brackets denote averaging over a cell). Then, the resulting quantities are averaged over all grid cells. In this manner, the effect of the average velocity on the thermal temperature is eliminated at each point, so that only the random motion contributes to the plasma temperature.[8,26]

At the initial time of the wave and particle interactions, the equivalent initial temperature, $T_{\kappa 0}$, is expressed as

$$T_{\kappa 0} = \frac{< mv_0^2 >}{3k_B} = \frac{2\kappa}{2\kappa - 3}\frac{m\theta^2}{2k_B}, \tag{9}$$

or equivalently

$$\theta = \left(\frac{2\kappa - 3}{2\kappa}\frac{2k_BT_{\kappa 0}}{m}\right)^{1/2}, \tag{10}$$

TABLE 1 Comparison of physical quantities associated with Kappa and Maxwellian distributions

Physical quantity	Kappa distribution ($\kappa > 3/2$)	Maxwellian distribution ($\kappa \to \infty$)
Average energy	$E_\kappa = \frac{1}{2N}\int f_\kappa(v)mv^2 d\mathbf{v}$	$E = \frac{1}{2N}\int f_m(v)mv^2 d\mathbf{v}$
Equivalent temperature	$T_\kappa = \frac{2}{3k_B}E_\kappa = \frac{<mv^2>}{3k_B}$	$T = \frac{2}{3k_B}E = \frac{<mv^2>}{3k_B}$
Initial equivalent temperature	$T_{\kappa 0} = \frac{<mv_0^2>}{3k_B} = \frac{2\kappa}{2\kappa-3}\frac{m\theta^2}{2k_B}$	$T_0 = \frac{<mv_0^2>}{3k_B} = \frac{mv_{th}^2}{2k_B}$
Initial average energy	$E_{\kappa 0} = \frac{3}{2}m\frac{2\kappa}{2\kappa-3}\frac{\theta^2}{2}$	$E_0 = \frac{3}{2}m\frac{v_{th}^2}{2}$
Characteristic speed	$\theta = \left(\frac{2\kappa-3}{2\kappa}\frac{2k_B T_{\kappa 0}}{m}\right)^{1/2}$	$v_{th} = \left(\frac{2k_B T_0}{m}\right)^{1/2}$
Rms of the initial velocities	$< v_{i0}^2 >_{i=x,y,z} = \frac{2\kappa}{2\kappa-3}\frac{\theta^2}{2}$	$< v_{i0}^2 >_{i=x,y,z} = \frac{v_{th}^2}{2}$

where θ is the practical characteristic speed, the same as in Equation (1) In the special case of $\kappa \to \infty$, *the practical* characteristic speed θ *and the* initial temperature $T_{\kappa 0}$ reduce to v_{th} and T_0, respectively. Similarly, the initial average energy per particle

$$E_{\kappa 0} = \frac{3}{2}k_B T_{\kappa 0} = \frac{3}{2}m\frac{2\kappa}{2\kappa - 3}\frac{\theta^2}{2}. \tag{11}$$

Clearly, with the isotropic three-dimensional Kappa distribution, the rms (root-mean-square) of the particle initial velocity becomes

$$< v_{i0}^2 >_{i=x,y,z} = \frac{< v_0^2 >}{3} = \frac{2\kappa}{2\kappa - 3}\frac{\theta^2}{2}. \tag{12}$$

The relationships between the Kappa and the Maxwellian distributions are summarized in Table 1.

3 | HEATING AND ACCELERATION OF IONS

First, we refer to the "stochastic heating" as defined by Wang et al.,[27] which is related to non-resonant heating. Wang et al.[27] pointed out that, after the non-resonant heating, as long as the wave amplitude exceeds the stochasticity threshold, ions are further heated and accelerated by stochastic processes. They also found that the stochastic heating for ions with Maxwellian velocity distribution is largely independent of the wave amplitude B_w^2. In contrast, the non-resonant heating is proportional to B_w^2 with either the Maxwellian distribution[7–11,14] or the Kappa distribution.[16] In this work, we also include the non-resonant and the stochastic heating with the Kappa distribution. The computed particle heating depends on the κ-parameter as shown in Figures 1 and 2. In the limit of $\kappa \to \infty$ (Maxwellian distribution), our results recover the findings that obtained by Wang et al.[27] Details are explained below.

The time evolution of the mean ion energy, normalized by $mv_A^2/2$, versus the normalized time $\Omega_0 t$, is shown in Figure 1. We choose the Alfvén wave amplitudes $B_w^2/B_0^2 = 0.15$, 0.20 and 0.25, all exceeding the stochasticity threshold. The ion energy is calculated by $E_\kappa =< mv^2 > /2 = (m/2)\sum_{i=x,y,z}\left\langle (v_i - \langle v_i \rangle)^2 \right\rangle$. Cases (a), (b), and (c) correspond to the Kappa distributions with $\kappa = 2, 3$ and the special case of $\kappa \to \infty$ (the Maxwellian velocity distribution), respectively. The final ion energy $E_{\kappa\,\max}$, defined as the "ion kinetic temperature T_{kin}" by Wang et al.,[27] reaches approximately an identical value of $mv_A^2/2$ at the end of the simulation. For the wave with large amplitude exceeding the stochasticity threshold, the heating is quantitatively close to that by Wang et al.[27] The larger the wave amplitude, the faster the ion energy approaches the asymptotic value. We find that the net heating energy of ions, in both non-resonant and stochastic heating, is determined by the Alfvén speed v_A. We also find that the final ion energy is not completely equal to $mv_A^2/2$, either with the Kappa distribution (for $\kappa = 2, 3$) or with the Maxwellian distribution. In fact the saturated energy is slightly larger than $mv_A^2/2$,

$$E_{\kappa\,\max} = \frac{3}{2}m\theta^2\frac{\kappa}{2\kappa - 3} + \frac{1}{2}mv_A^2 = E_{\kappa 0} + \frac{1}{2}mv_A^2. \tag{13}$$

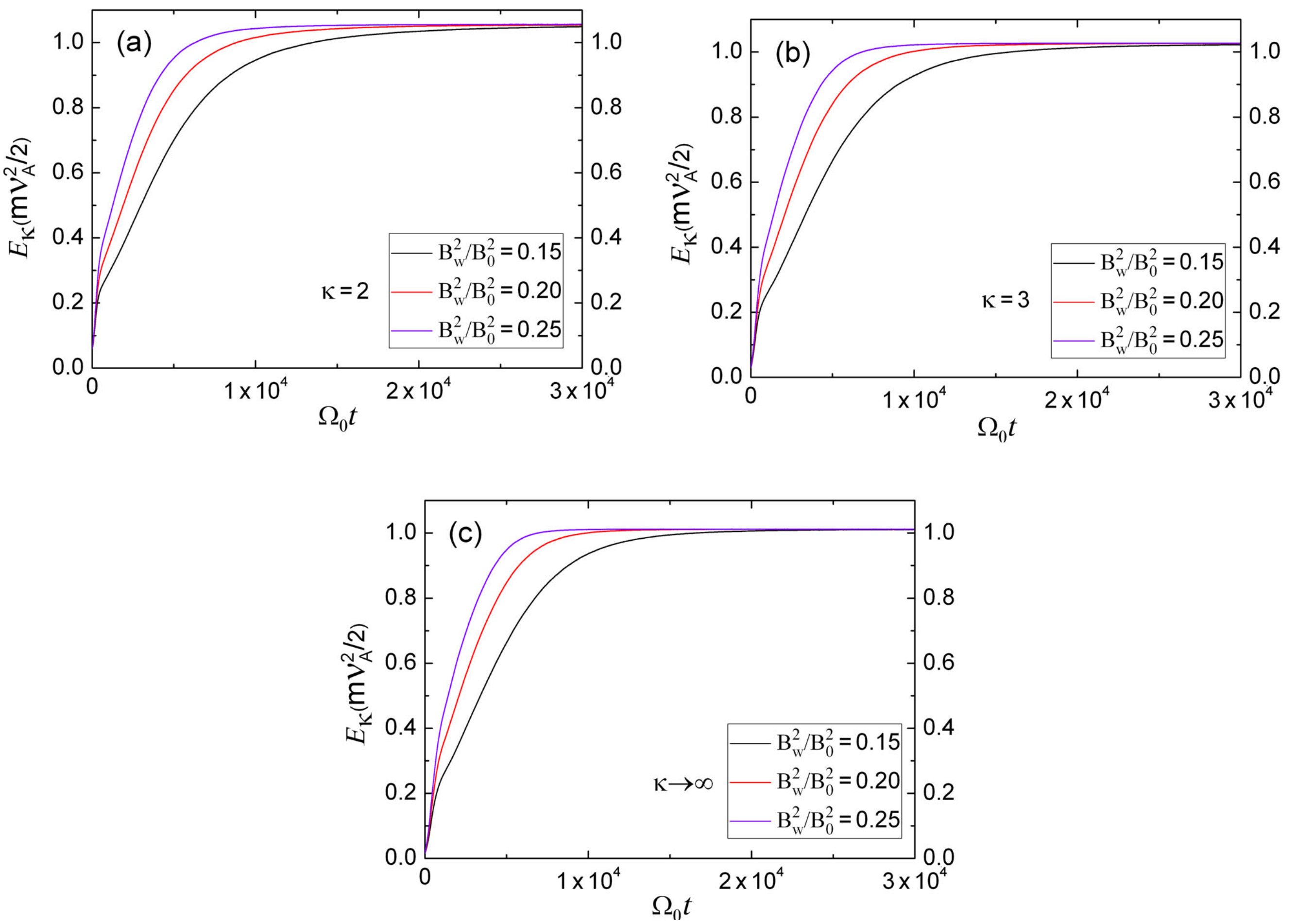

FIGURE 1 The time evolution of the mean ion energy, normalized by $mv_A^2/2$, versus the normalized time $\Omega_0 t$

Figure 1 shows (cases (a), (b), and (c) for $\kappa = 2, 3$, and $\kappa \to \infty$) the initial and final ion energies normalized by $mv_A^2/2$, $(E_{\kappa 0}, E_{\kappa\,\max})$, being approximately equal to (0.06, 1.06), (0.03, 1.03), and (0.015, 1.015), for the cases (a), (b), and (c), respectively. We set the initial characteristic speed $\theta^2 = 1$ and $\beta = (\theta/v_A)^2 = 0.01$. It is worth noting that the obtained net heating energy of ions is $mv_A^2/2$, but the final energy is $E_{\kappa 0} + mv_A^2/2$. Equation (13) can be further converted to

$$E_{\kappa\,\max} = E_{\kappa 0} + \frac{B_0^2}{2\mu_0 n_0} = E_{\kappa 0} + \frac{W_0}{n_0}, \tag{14}$$

by making use of the definition of the Alfvén wave phase speed $v_A = B_0/\sqrt{\mu_0 n_0 m}$, and the ambient magnetic field energy density $W_0 = B_0^2/(2\mu_0)$.[9,10] Equation (14) shows that the final energy of ions depends on their initial energy and the ratio of the magnetic field energy density to the plasma density, but is not related to the Alfvén wave frequency nor the amplitude. This holds as long as the stochastic heating condition is satisfied.

Figure 2 plots the average parallel velocity of ions, with the same parameters as in Figure 1. At the initial stage of heating, the "shaded area" appears, because the non-resonant heating is not yet fully developed. The temperatures oscillate before reaching the characteristic time scale $\pi/(k\theta)$.[8] For $\omega = 0.0375\Omega_0$, the characteristic time scale is about $837\Omega_0^{-1}$. At this point, the curves become smooth, reaching individual values of parallel velocity, which roughly follow the analytic prediction of $v_\parallel = v_A\left(B_w^2/B_0^2\right)$.[8,16] The results are consistent with the theoretical analysis and with the simulation results of Lu & Li[8] and Liu et al.,[16] but do not agree with the multi-wave simulation results by Wang et al.[27] Exiting the "shaded area," the curves saturate towards the Alfvén speed v_A, independent of the wave amplitude, though the saturation process itself is faster with larger wave amplitude, and with higher κ-value in the initial distribution.

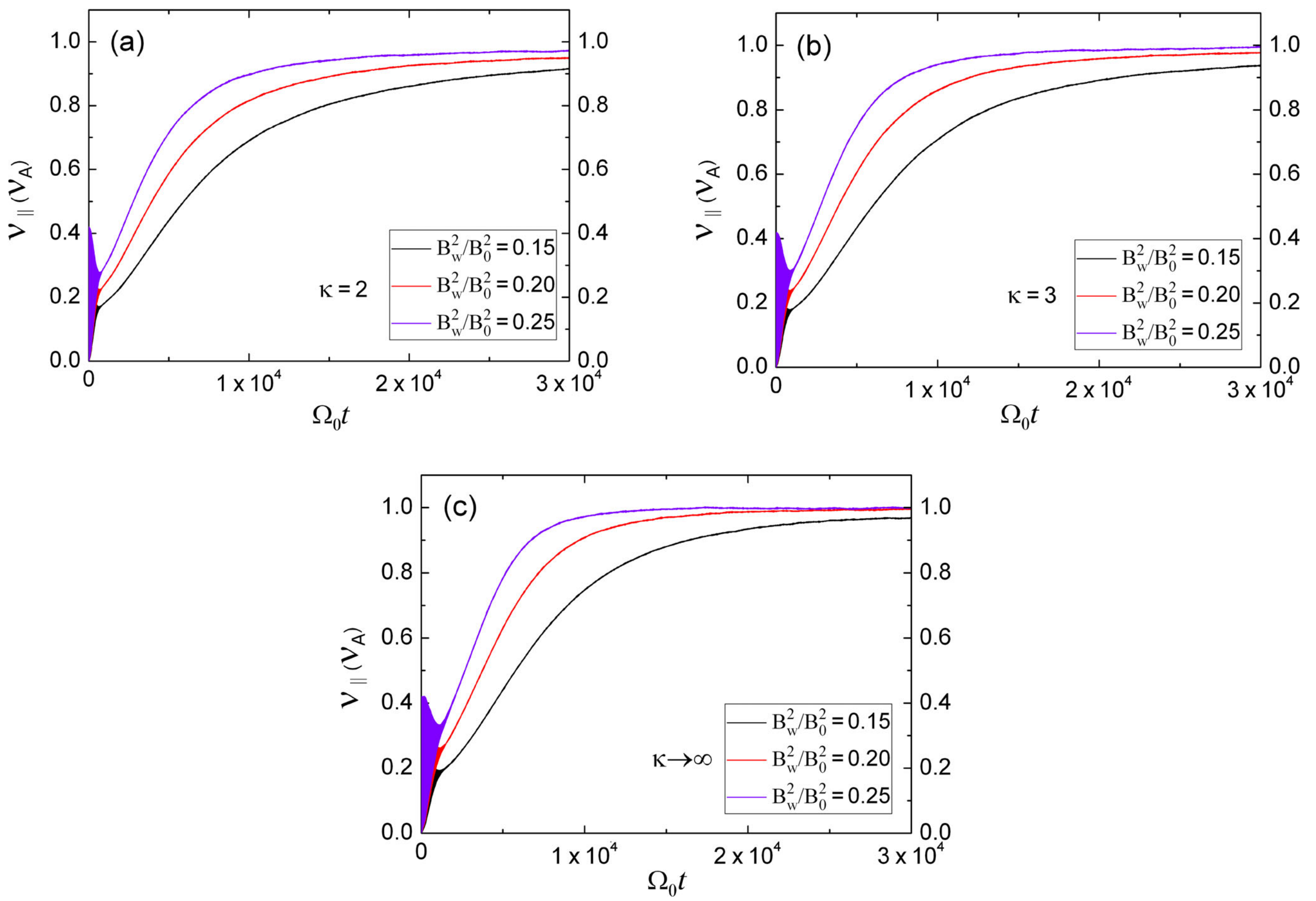

FIGURE 2 The average parallel velocity of ions, normalized by v_A, with the same parameters as in Figure 1

Now, we focus on the temporal behaviour of the "equivalent temperature" of the plasma. The equation of energy is rigorously applied. Rewriting of Equation (13) yields

$$\frac{3}{2}k_B T_{\kappa\,\max} = \frac{3}{2}k_B T_{\kappa 0} + \frac{1}{2}mv_A^2, \tag{15}$$

$$T_{\kappa\,\max} = T_{\kappa 0} + \frac{m}{3k_B}v_A^2 = T_{\kappa 0} + \frac{m}{3k_B}\frac{\theta^2}{\beta} = T_{\kappa 0}\left(1 + \frac{2\kappa - 3}{\kappa}\frac{1}{3\beta}\right), \tag{16}$$

where we have made use of the relation $\theta^2 = (k_B T_{\kappa 0}/m)(2\kappa - 3)/\kappa$. This shows that the maximum heating effect of the Kappa ions depends on parameter κ of the initial distribution and on the beta value. Simulation results strongly agree with the above analytic prediction, as shown in Figure 3, where cases (a) and (b) correspond to the Alfvén wave amplitude of $B_w^2/B_0^2 = 0.15$ and 0.25, respectively. As examples, we choose the parameters κ of 2, 3, 6, and $\kappa \to \infty$, respectively. The final "equivalent temperatures" of the plasma are.

$$\kappa = 2, T_{\kappa\,\max} = T_{\kappa 0}\left(1 + \frac{1}{6\beta}\right) = 17.7T_{\kappa 0}; \tag{17a}$$

$$\kappa = 3, T_{\kappa\,\max} = T_{\kappa 0}\left(1 + \frac{1}{3\beta}\right) = 34.3T_{\kappa 0}; \tag{17b}$$

$$\kappa = 6, T_{\kappa\,\max} = T_{\kappa 0}\left(1 + \frac{1}{2\beta}\right) = 51T_{\kappa 0}; \tag{17c}$$

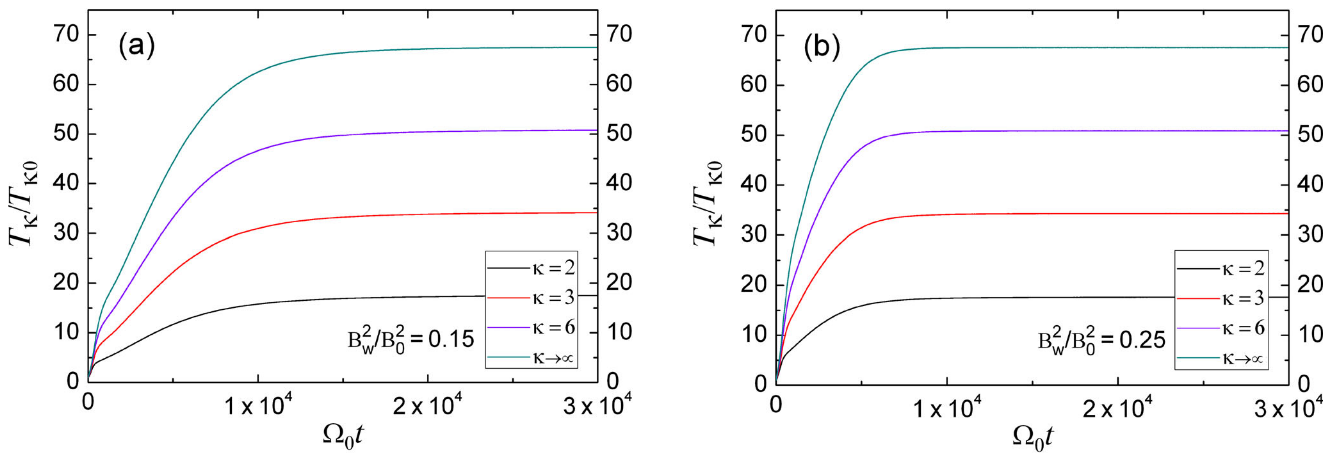

FIGURE 3 The time evolution of the "equivalent temperature" of the plasma, normalized by $T_{\kappa 0}$, where cases (a) and (b) corresponds to the Alfvén wave amplitude of $B_w^2/B_0^2 = 0.15$ and 0.25, respectively

$$\kappa \to \infty, T_{\max} = T_0\left(1 + \frac{2}{3\beta}\right) = 67.7T_0. \tag{17d}$$

The above heating process is almost the same when the wave amplitude reaches a threshold value. To further illustrate the non-resonant and the stochastic wave-particle interaction process, we consider one case with the Alfvén wave amplitude of $B_w^2/B_0^2 = 0.15$ and with the Maxwellian distribution, as shown in Figure 4. The time evolution of the proton velocity distribution satisfies the energy conservation equation in the Alfvén wave frame[50]

$$v_\perp^2(t) + \left[v_\parallel(t) - v_A\right]^2 = v_\perp^2(0) + \left[v_\parallel(0) - v_A\right]^2, \tag{18}$$

where $v_\perp$ and $v_\parallel$ stand for velocity components perpendicular and parallel to the ambient magnetic field. Figure 4 shows the proton velocity distribution, in the laboratory frame, during the heating process at $\Omega_0 t = 0, 250, 1{,}000, 2{,}500, 5{,}000$, and 25,000, respectively. Initially, the velocity distribution is three-dimensional isotropic Maxwellian, with the characteristic speed $v_{th} = 0.1v_A$. The three directional average speed of the proton's is zero, as shown by the solid sphere centred at (0, 0, 0) in Figure 4a. At $\Omega_0 t = 250$, protons are picked up in the transverse direction by the Alfvén wave and an average transverse velocity is obtained. In other words, ions non-resonant heating occurs as shown in Figure 4b. At $\Omega_0 t = 1{,}000$, protons in the vertical direction are captured by the Alfvén wave. In the direction of propagation along the Alfvén wave, ions gain an average speed due to the effect of phase mixing and the subsequent heating by wave-particle non-resonant interaction.[8,14] Afterward, when the wave amplitude satisfies the stochastic threshold, the regular movement of protons transfers to chaotic action. The non-resonance overlap in phase space results in randomization in the particle distribution, and the stochastic heating starts to occur. In this stage of heating, protons in the velocity space have half sphere distribution due to pitch angle scattering. The specific process of pitch angle scattering is shown in Figure 4c–f. At $\Omega_0 t = 25{,}000$, the centre of the spherical shell distribution is $(0, 0, 1.0)v_A$, the ion parallel velocity distributes in the range of $(0 \sim 2.0)v_A$. The ions attain a bulk parallel speed, which is roughly equal to v_A. The motion of ions on the spherical surface in the velocity space, defined by Equation (18), is attributed to pitch angle scattering.[27]

4 | SUMMARY

In this paper, heating and acceleration of low-beta plasma ions with initial Kappa distribution, by a low-frequency LH polarization Alfvén wave, has been studied by means of test-particle approach. As long as the Alfvén wave amplitude exceeds the stochasticity threshold, the net heating energy obtained by ions is $mv_A^2/2$. This process is equivalent to the protons gaining a net average parallel speed. In particular, the bulk speed is roughly equal to the Alfvén speed, $v_\parallel \approx v_A$, in the laboratory frame. We made detailed study of the physical processes associated with the non-resonant and stochastic heating. The asymptotically independent heating is due to the pickup process that involves the formation of spherical shell velocity distribution function as a result of the pitch angle scattering.

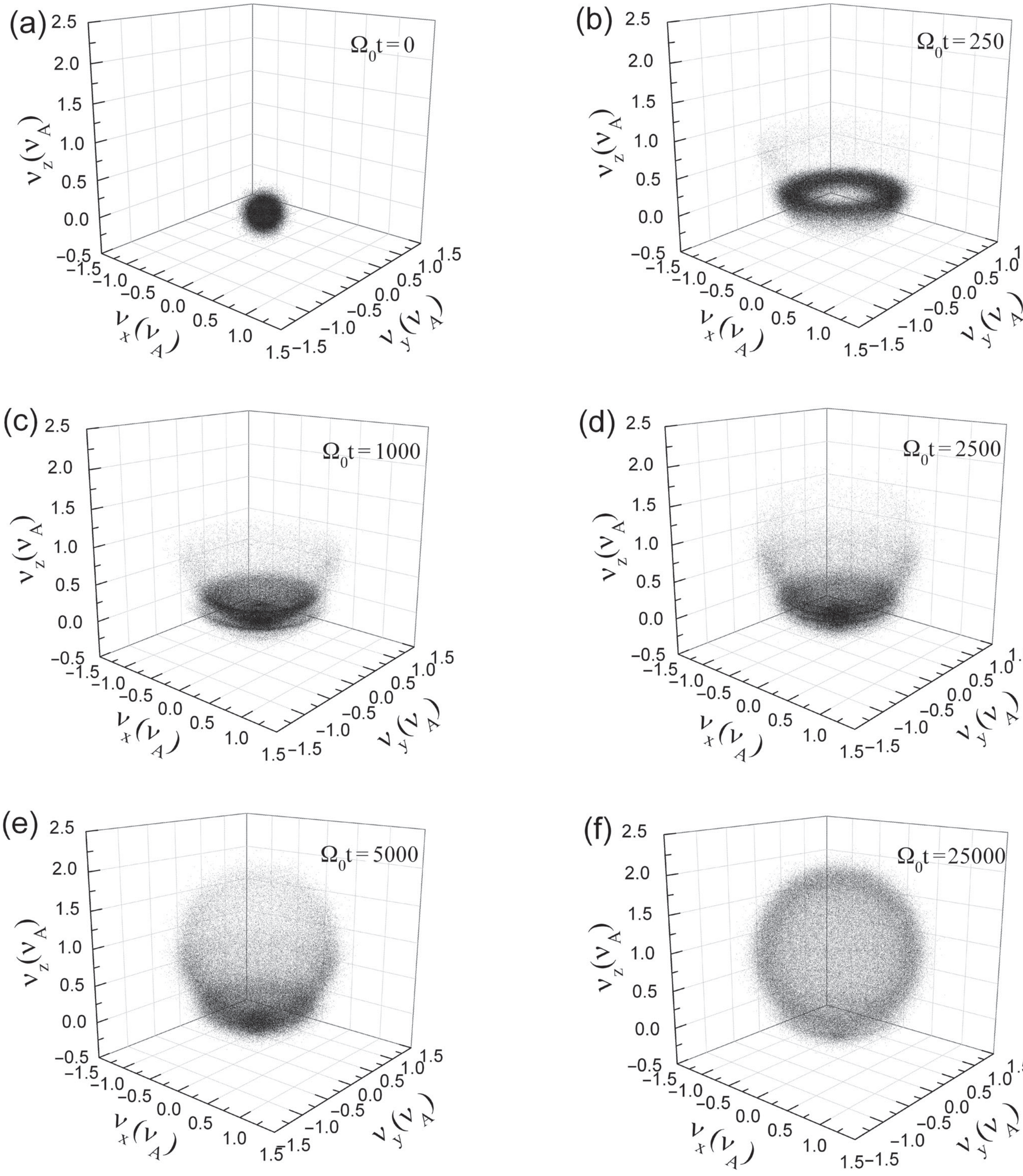

FIGURE 4 The proton velocity distribution, in the laboratory frame, during the heating process at $\Omega_0 t$ = 0, 250, 1,000, 2,500, 5,000, and 25,000, respectively

The main results are summarized as follows: (a) the final energy of ions depends on the initial energy and on the ratio of the magnetic field energy density to the plasma density, but does not depend on the Alfvén wave frequency and amplitude; (b) at the saturation stage of the simulation, the average $v_{\parallel}$ approaches v_A. Larger wave amplitude and higher κ value of the initial distribution lead to faster saturation towards the Alfvén speed; (c) the final heating of Kappa ions depends on the parameter κ of the initial distribution and on the beta value. The final heating increases with κ, and as $\kappa \to \infty$, it becomes identical to that of the Maxwellian distribution.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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