ION PICKUP BY FINITE AMPLITUDE PARALLEL PROPAGATING ALFVÉN WAVES

XING LI,[1] QUANMING LU,[2] AND BO LI[1]

ABSTRACT

Two scenarios of possible ion heating due to finite amplitude parallel propagating Alfvén waves in the solar atmosphere are investigated using a one-dimensional test particle approach. (1) A finite amplitude Alfvén wave is instantly introduced into a plasma (or equivalently, new ions are instantly created). (2) New ions are constantly created. In both scenarios, ions will be picked up by the Alfvén wave. In case 1, the wave scatters ions in the transverse direction leading to a randomization (or heating) process. This process is complete when a phase shift of $\pm\pi$ in the ion gyrospeed is produced between particles with characteristic parallel thermal speed and particles with zero parallel speed. This corresponds to $t = \pi/kv_{\rm th}$ (k is the wavenumber, and $v_{\rm th}$ is the ion thermal speed). A ring velocity distribution can be produced for a large wave amplitude. The process yields a mass-proportional heating in the transverse direction, a temperature anisotropy, and a bulk flow along the background magnetic field. In case 2, continuous ion creation represents a continuing phase shift in the ion gyrospeed leading to heating. New particles are picked up by the Alfvén wave within one ion gyroperiod. It is speculated that the mechanism may operate in the chromosphere and active regions where transient events may generate finite amplitude Alfvén waves.

Subject headings: Sun: chromosphere — Sun: corona — waves

1. INTRODUCTION

It has been widely speculated that the energy that heats the corona comes from the convective flows in the photosphere. The energy is somehow transported into the coronal part through the magnetic field. It is natural to think that Alfvén waves channel the energy to the corona. Indeed, these waves have been observed in the solar atmosphere (Ulrich 1996) and are ubiquitous in the extended corona—the fast solar wind (Smith et al. 1995). However, Alfvén waves are difficult to dissipate in collisionless plasmas. Hence, nonlinear processes have been assumed to cascade the wave energy from low to high frequencies where wave dissipation is readily possible (Hollweg 1986; Li & Habbal 2003).

When Alfvén waves propagate in a partially ionized plasma, neutral-ion collisions produce a channel for the wave dissipation (De Pontieu & Haerendel 1998; De Pontieu et al. 2001; Leake et al. 2005). Ions and neutrals can be collisionally coupled. A slippage between the ion and neutral populations leads to the wave dissipation. If we consider that neutrals are constantly ionized at the chromosphere, we will show that these newly created He^{+1} ions will be picked up by the wave and will be energized.

In this Letter, a new scenario, ion pickup by an Alfvén wave, is explored. The pickup process can lead to the heating of ions, and it must also dissipate the wave. In § 2, we discuss the ion pickup process by an instantly introduced wave (or identically, the ions are created instantly). In § 3, the pickup of continuously created ions by an Alfvén wave is investigated. Finally, in § 4 we discuss possible applications of the ion pickup process in the solar atmosphere.

2. ION PICKUP BY ALFVÉN WAVES

Consider a parallel propagating monochromatic dispersionless Alfvén wave with angular frequency ω and wavenumber

[1] Institute of Mathematical and Physical Sciences, University of Wales, Aberystwyth, UK.
[2] University of Science and Technology of China, Hefei, Anhui, China.

k, and $\omega = kv_A$ (v_A is the Alfvén speed). The wave electromagnetic field $\delta\boldsymbol{B}_w$ and $\delta\boldsymbol{E}_w$ are

$$\delta\boldsymbol{B}_w = B_k(\cos\phi_k\boldsymbol{i}_x - \sin\phi_k\boldsymbol{i}_y),$$
$$\delta\boldsymbol{E}_w = -v_A\boldsymbol{B}_0/B_0 \times \delta\boldsymbol{B}_w, \tag{1}$$

where $\boldsymbol{i}_x$ and $\boldsymbol{i}_y$ are unit vectors, B_0 is the background magnetic field, and $\phi_k = k(v_A t - z)$ denotes the wave phase. The motion of a particle is described by

$$m_j\frac{d\boldsymbol{v}}{dt} = e_j[\delta\boldsymbol{E}_w + \boldsymbol{v} \times (B_0\boldsymbol{i}_z + \delta\boldsymbol{B}_w)], \quad \frac{dz}{dt} = v_z. \tag{2}$$

Let $u_\perp = v_x + iv_y$, $v_\parallel = v_z$, and $\delta B_w = B_k e^{-i\phi_k}$; then we have

$$\frac{du_\perp}{dt} + i\Omega_0 u_\perp = i(v_\parallel - v_A)\Omega_k e^{-i\phi_k}, \tag{3}$$

$$\frac{dv_\parallel}{dt} = -\text{Im}\,(u_\perp\Omega_k e^{i\phi_k}), \quad \frac{dz}{dt} = v_\parallel, \tag{4}$$

where $\Omega_0 = e_j B_0/m_j$, $\Omega_k = e_j B_k/m_j$, and j refers to the physical quantities of ion species j. As a first-order approximation, $v_\parallel \approx v_\parallel(0)$ is a constant, where $v_\parallel(0)$ is the initial ion parallel velocity. The approximation is valid when $\Omega_k/\Omega_0 = B_k/B_0$ is small and the wave frequency is low so $|\Omega_0| \gg |k(v_\parallel - v_A)|$. With the initial condition $u_\perp = u_\perp(0)$ and $z = z(0)$, the solution of equation (3) for a low beta plasma is (Wu et al. 1997; Lu et al. 2006)

$$u_\perp = \left[u_\perp(0) + v_A\frac{B_k}{B_0}e^{ikz(0)}\right]e^{-i\Omega_0 t} - v_A\frac{B_k}{B_0}e^{-ik(v_A t - z)}, \tag{5}$$

where $z = z(0) + v_\parallel(0)t$ and we have adopted approximations $\Omega_0 - k[v_A - v_\parallel(0)] \approx \Omega_0$, $v_A - v_\parallel(0) \approx v_A$. The last term of $u_\perp$ is the perturbed ion velocity of an Alfvén wave. The first term

is due to the gyromotion of the particle and the modification of the gyromotion due to the wave. Note, if $u_\perp(0) = -v_A(B_k/B_0)e^{-ikz(0)}$ and $v_\parallel(0) = 0$, the particle is surfing on the wave, and there is no gyromotion.

Now let us consider an ensemble of newly created particles with a Maxwellian distribution. The particles' average parallel speed is zero, but the transverse component is $u_{\perp f}$:

$$u_\perp(0) = u_{\perp r}(0) + u_{\perp f}(0) = u_{\perp r}(0) - \alpha v_A \frac{B_k}{B_0} e^{ikz}, \quad (6)$$

where α, a constant, describes the degree that the newly created particles are settled in the wave field. If $\alpha = 1$, the newly created particles are already settled; $u_{\perp r}$ denotes the random perpendicular thermal speed. After time t, particles with different initial position $z(0) = z - v_\parallel(0)t$ will arrive at z. The average transverse velocity at z is

$$U_\perp = -v_A \frac{B_k}{B_0} e^{-ik(v_A t - z)} + \frac{1 - \alpha}{\sqrt{\pi} v_{th}}$$

$$\times \int_{-\infty}^{\infty} v_A \frac{B_k}{B_0} e^{ik[z - v_\parallel(0)t]} e^{-i\Omega_0 t} e^{-[v_\parallel(0)/v_{th}]^2} dv_\parallel(0)$$

$$= -v_A \frac{B_k}{B_0} e^{-ik(v_A t - z)} + (1 - \alpha) A_k v_A \frac{B_k}{B_0} e^{ikz} e^{-i\Omega_0 t}, \quad (7)$$

where $A_k = 1/\sqrt{\pi} \int_{-\infty}^{\infty} \cos(kv_{th} tx) e^{-x^2} dx = e^{-k^2 v_{th}^2 t^2/4}$, $v_{th} = (2k_B T_{j0}/m_j)^{1/2}$, and T_{j0} is the initial temperature of species j. Equation (7) illustrates the pickup of ions by the wave. Note $A_k \approx 0$ when $kv_{th} t \gtrsim \pi$. Hence, regardless of the value of α, these particles will be picked up by the Alfvén wave: eventually $U_\perp$ is determined by the wave only. Subtracting equation (7) from equation (5), one finds the random perpendicular velocity at z:

$$u_\perp - U_\perp = u_{\perp r}(0) e^{-i\Omega_0 t} + (1 - \alpha) v_A \frac{B_k}{B_0} e^{ik[z - v_\parallel(0)t]} e^{-i\Omega_0 t}$$

$$- (1 - \alpha) A_k v_A \frac{B_k}{B_0} e^{i(kz - \Omega_0 t)}. \quad (8)$$

Equation (8) describes the particles' gyrospeed in the frame of $U_\perp$. When $\alpha = 0$ (initially the newly created particles have zero flow speed), particles will be strongly scattered in the phase space. The second term on the right-hand side is crucial for our understanding the heating in the pickup process. In the phase-space frame of $U_\perp$, a randomization process is complete when particles with characteristic speed $v_\parallel(0) = \pm v_{th}$ moving from $z(0) = z - v_\parallel(0)t$ to z are scattered in the perpendicular direction and a phase shift $\pm \pi$ in the gyrospeed relative to particles with $v_\parallel(0) = 0$ is produced. This translates to $kv_{th} t \approx \pi$. For a finite amplitude Alfvén wave, if $v_A B_k/B_0 > v_{th}$, the distribution function will be a ring. Hence, particles are strongly heated. On the other hand, if $\alpha = 1$, initially particles are already "picked up" by (surfing on) the wave. Only the initial random motion survives, and there is no heating. One notices that if $v_{th} = 0$, $A_k = 1$,

there is also no heating. Hence, the heating is a warm plasma effect. With $U_\perp$, the perpendicular temperature can be found:

$$T_{\perp j} = \frac{m_j}{2k_B v_{th} \sqrt{\pi}} \int_{-\infty}^{\infty} |u_\perp - U_\perp|^2 e^{-[v_\parallel(0)/v_{th}]^2} dv_\parallel(0)$$

$$= T_{j0} \left[1 + \frac{m_j B_k^2}{m_p \beta_j B_0^2} (1 - A_k^2)(1 - \alpha)^2 \right], \quad (9)$$

where $\beta_j = 8\pi n_e k_B T_{j0}/B_0^2$ is the plasma beta of species j. The heating is obviously mass-proportional.

Substituting equation (5) into equation (4), and letting $v_A - v_\parallel(0) \approx v_A$ and $\Omega_0 - k[v_A - v_\parallel(0)] \approx \Omega_0$, one finds

$$v_\parallel = v_\parallel(0) + v_A(1 - \alpha) \frac{B_k^2}{B_0^2} \{1 - \cos[\Omega_0 t - kv_A t - kv_\parallel(0)t]\},$$

$$(10)$$

Using the same procedure to obtain $U_\perp$ and $T_\perp$, we find the average parallel velocity and temperature:

$$U_\parallel = v_A \frac{B_k^2}{B_0^2} (1 - \alpha)[1 - A_k \cos(\Omega_0 t - kv_A t)], \quad (11)$$

$$T_{\parallel j} = T_{j0} \left\{ 1 + \frac{2m_j B_k^4 (1 - \alpha)^2}{m_p \beta_j B_0^2} [(C_k - A_k^2) \cos^2(\Omega_0 t - kv_A t) \right.$$

$$\left. + (1 - C_k) \sin^2(\Omega_0 t - kv_A t)] \right\},$$

$$(12)$$

where $C_k = 1/\sqrt{\pi} \int_{-\infty}^{\infty} \cos^2(kv_{th} tx) e^{-x^2} dx = 0.5 + 0.5e^{-k^2 v_{th}^2 t^2}$. When $t \to \infty$, $A_k = 0$ and $C_k = 0.5$. We then obtain asymptotic values:

$$U_\perp = -v_A \frac{B_k}{B_0} e^{-ik(v_A t - z)}, \quad U_\parallel = v_A(1 - \alpha) \frac{B_k^2}{B_0^2}, \quad (13)$$

$$T_{\perp j} = T_{j0} \left[1 + \frac{(1 - \alpha)^2 m_j B_k^2}{m_p \beta_j B_0^2} \right],$$

$$T_{\parallel j} = T_{j0} \left[1 + \frac{m_j B_k^4 (1 - \alpha)^2}{m_p \beta_j B_0^4} \right]. \quad (14)$$

Subtracting equation (11) from equation (10), when $t \to \infty$, one finds

$$v_\parallel - U_\parallel = v_\parallel(0) + v_A(1 - \alpha) \frac{B_k^2}{B_0^2} \cos[\Omega_0 t - kv_A t - kv_\parallel(0)t].$$

$$(15)$$

It is possible that the second term on the right-hand side is larger than the initial random thermal velocity $v_\parallel(0)$. In this case, the velocity distribution plotted in the $v_\parallel$-v_y plane may be a ring as well (see Fig. 2).

To verify the above analysis, a test particle simulation was conducted by calculating the full dynamics of particles (eq. [2])
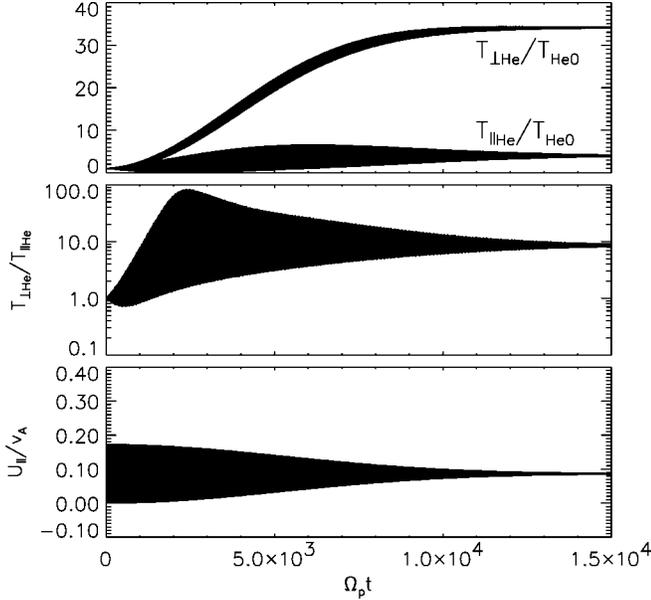
FIG. 1.—Time history of the perpendicular temperature $T_{\perp \mathrm{He}}/T_{\mathrm{He0}}$ and the parallel temperature $T_{\parallel \mathrm{He}}/T_{\mathrm{He0}}$ (*top*), the temperature anisotropy $T_{\perp \mathrm{He}}/T_{\parallel \mathrm{He}}$ (*middle*), and the average parallel velocity $U_{\parallel}/v_{\mathrm{A}}$ (*bottom*). Here we choose the particle as He^{+1}, and the parameters are $\alpha = 0$, $\omega/\Omega_p = 0.25\pi/125 \approx 0.0063$, $\beta_{\mathrm{He}} = 0.01$, $B_k^2/B_0^2 = 0.09$.

in the electromagnetic field of a given Alfvén wave described by equation (1). The equations were solved using the Boris algorithm with time step $\Delta t = 0.01\Omega_p^{-1}$ (Ω_p is the proton gyrofrequency) and periodic boundary conditions. Initially, 200,000 particles with Maxwellian velocity distribution were evenly distributed in a region with length $1000v_A\Omega_p^{-1}$ (1000 cells). The flow speed of these particles was zero. The average parallel velocity, and the parallel and perpendicular temperatures, were obtained by using the following procedure: we first computed $U_{\parallel} = \langle v_z \rangle$, $T_{\parallel} = (m_j/k_B)\langle(v_z - \langle v_z \rangle)^2\rangle$, and $T_{\perp} = (m_j/2k_B)\langle(v_x - \langle v_x \rangle)^2 + (v_y - \langle v_y \rangle)^2\rangle$ in every cell (angle brackets denote an average over a cell). These quantities were then averaged over all cells, so only random motions contribute to the temperatures. Figure 1 shows the time evolution of the perpendicular temperature $T_{\parallel \mathrm{He}}/T_{\mathrm{He0}}$ (here 0 refers to the initial value) and the parallel temperature $T_{\perp \mathrm{He}}/T_{\mathrm{He0}}$ (*top*), the temperature anisotropy $T_{\perp}/T_{\parallel}$ (*middle*), and the average parallel velocity $U_{\parallel}/v_{\mathrm{A}}$ of the test particle simulation (*bottom*). The shaded areas are due to rapid ion gyrations. The results are consistent with our analytical predictions. At $\Omega_p t \approx 12{,}000$, an asymptotic stage is reached: $U_{\parallel}/v_{\mathrm{A}} \approx 0.086$, $T_{\perp \mathrm{He}}/T_{\mathrm{He0}} \approx 34$, and $T_{\parallel \mathrm{He}}/T_{\mathrm{He0}} \approx 3.9$ with the temperature anisotropy $T_{\perp \mathrm{He}}/T_{\parallel \mathrm{He}} \approx 8.7$.

Figure 2 displays scatter plots of the helium ions in the five cells around $z = 500v_A\Omega_p^{-1}$ at $\Omega_p t = 0$, 2800, 6600, and 11,000. Initially, helium ions satisfy the Maxwellian distribution with $v_{\mathrm{th}} = 0.005v_A$ and $\beta_{\mathrm{He}} = 0.01$. Helium ions are dramatically scattered in the transverse direction in the phase space. The ring velocity distributions are nicely shown in Figure 2. The ring velocity distribution is unstable (Lu & Wang 2005). The velocity distribution may eventually be thermalized by relevant microscopic instabilities of the ring distribution. The bulk acceleration of particles along $\boldsymbol{B}_0$ is obvious. This is because in the frame of the Alfvén phase speed, the kinetic energy of particles is conserved. As particles are picked up by the wave, they gain a bulk acceleration along $\boldsymbol{B}_0$.
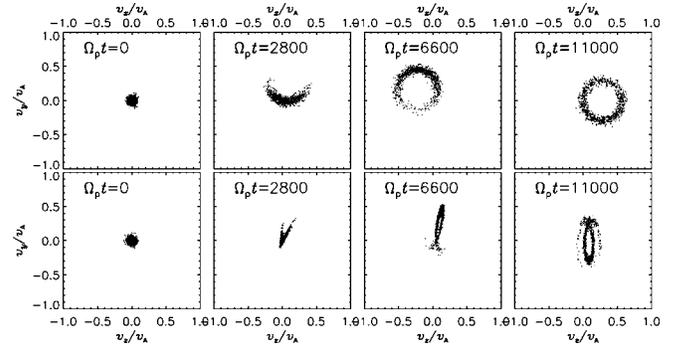
FIG. 2.—*Top panel*: Scatter plots of helium He^{+1} velocity in the velocity plane perpendicular to $v_{\parallel}$. *Bottom panel*: Scatter plots of helium He^{+1} velocity in the plane parallel to the background magnetic field. Relevant parameters are those in Fig. 1.

3. PICKUP OF CONTINUOUSLY CREATED IONS

In a partially ionized plasma, the creation of new ions due to photoionization or collisional ionization is highly random. Consider a region with a low plasma beta and where the amplitude of an Alfvén wave is finite. When ions are created from neutrals, they are subject to rapid gyromotions. The continuous creation of ions represents a continuous phase shift in the ion gyrospeed. This will naturally mix the phase of particles' gyrospeeds. To explore the pickup process of continuously created ions, a new test particle simulation is conducted. The Alfvén wave and the simulation box are the same as in § 2. However, 1000 particles are deployed every $0.25\Omega_p^{-1}$ at $0 \leq \Omega_p t \leq 100$ (one particle per cell). The beta value of the newly created He^{+1} ions is 0.01, and they have zero flow speed. The results of the simulation are shown in Figures 3 and 4, which are plotted in the same way as Figures 1 and 2. Note that in the v_x-v_y plane, because the radius of the ring (Fig. 3) is $B_k v_A/B_0$, the origin, where new particles are created around there, is always on the ring. When new He^{+1} ions are continuously
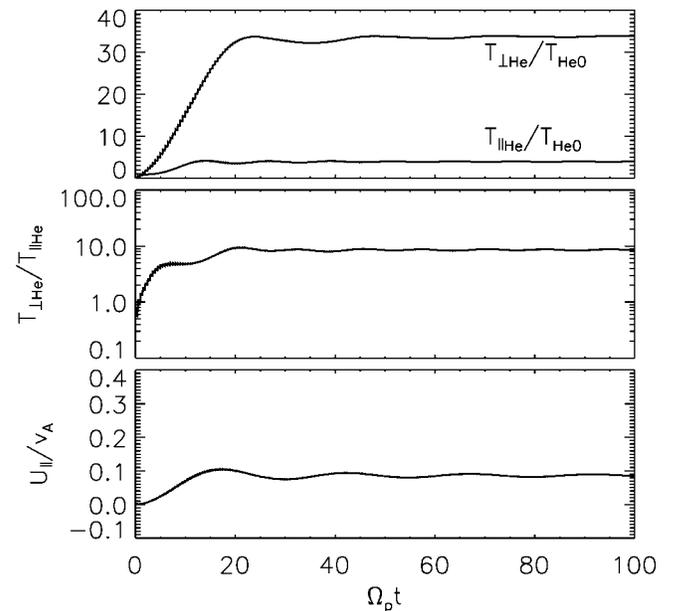
FIG. 3.—Time history of $T_{\perp \mathrm{He}}/T_{\mathrm{He0}}$ and $T_{\parallel \mathrm{He}}/T_{\mathrm{He0}}$ (*top*), $T_{\perp \mathrm{He}}/T_{\parallel \mathrm{He}}$ (*middle*), and $U_{\parallel}/v_{\mathrm{A}}$ (*bottom*). Here $kv_A/\Omega_p = 0.25\pi/125 \approx 0.0063$, $\beta_{\mathrm{He}} = 0.01$, $B_k^2/B_0^2 = 0.09$. The He^{+1} ions are steadily and uniformly created between $z = 0$ and $1000v_A\Omega_p^{-1}$ at $0 < \Omega_p t < 100$.
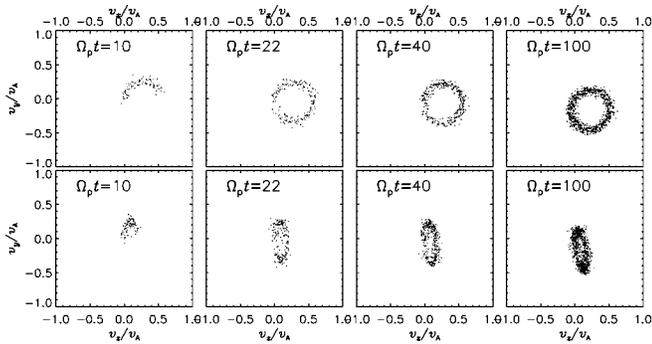
FIG. 4.—*Top panel*: Scatter plots of helium He^{+1} velocity in the velocity plane perpendicular to $v_\parallel$. *Bottom panel*: scatter plots of helium He^{+1} velocity in the plane parallel to the background magnetic field. Relevant parameters are those in Fig. 3.

created, the heating and scattering process are completed when they have filled the ring of radius $B_k v_A / B_0$ in the v_x-v_y plane. This only takes one gyroperiod of He^{+1} ions, or when $\Omega_p t = 8\pi$, as shown in Figures 3 and 4. Hence, the heating of these particles is extremely rapid. The ion creation process was terminated at time $t = 100 \Omega_p^{-1}$; however, no change is observed as $\Omega_p t \geq 8\pi$. We believe that the rapid heating due to Alfvén waves reported by Wang et al. (2006) is due to their deployment of particles within one gyroperiod, even though they used many wave modes in their computations.

4. DISCUSSION FOR POTENTIAL APPLICATIONS

The Alfvén wave pickup of newly created ions may have applications at the top of the chromosphere or the lower transition region. Let us consider the region with an ion cyclotron frequency much higher than Coulomb collision frequencies, low plasma beta, and finite amplitude Alfvén waves. For neutral helium, when wave frequencies are higher than the ion neutral collision frequencies, the perturbed ion and neutral velocity will have a considerable difference between their phases and amplitudes (De Pontieu & Haerendel 1998). In coronal funnels, the plasma beta at the lower transition region is much smaller than unity (Li 2003). For finite amplitude waves, the pickup process described above may operate and heat newly created He^{+1} ions. Due to collisions, the temperature is not expected to reach the value given by equation (14). Instead, the energy will be transferred to protons and electrons via Coulomb coupling. Obviously, the thermal energy of He^{+1} gained through the pickup process will be passed to He^{+2} later on when He^{+2} are created. As the ionization continues to the transition region (Hansteen et al. 1997), the pickup process will contribute to the plasma heating there.

The pickup of instantly created ions by an Alfvén wave or the pickup of ions by an Alfvén wave instantly introduced into a plasma is quite efficient even for low-frequency waves in collisionless plasmas. The pickup process is complete when $k v_{th} t = \pi$ or $t = (v_A / 2 v_{th}) t_A$, where t_A is the period of the wave. Transverse oscillations of active region coronal loops that suddenly appear with periods of 2–33 minutes have been frequently observed by the *Transition Region and Coronal Explorer* (Nakariakov et al. 1999; Aschwanden et al. 2002). The oscillations usually just last several wave periods. The relative amplitude B_k / B_0 of these waves can reach 0.05 (Aschwanden et al. 2002). For a typically observed 10^6 K coronal loop with a density of 10^9 cm^{-3} and a magnetic field of 30 G, the plasma beta value is 0.00385. Due to the pickup process, the perpendicular temperature of helium ions and oxygen ions may be increased to 3.6 and 11.4 times their original values, respectively.

REFERENCES

Aschwanden, M. J., De Pontieu, B., Schrijver, C. K., & Title, A. M. 2002, Sol. Phys., 206, 99
De Pontieu, B., & Haerendel, G. 1998, A&A, 338, 729
De Pontieu, B., Martens, P. C. H., & Hudson, H. S. 2001, ApJ, 558, 859
Hansteen, V. H., Leer, E., & Holzer, T. E. 1997, ApJ, 482, 498
Hollweg, J. V. 1986, J. Geophys. Res., 91, 4111
Leake, J. E., Arber, T. D., & Khodachenko, M. L. 2005, A&A, 442, 1091
Li, X. 2003, A&A, 406, 345
Li, X., & Habbal, S. R. 2003, ApJ, 598, L125

Lu, Q. M., & Wang, S. 2005, Geophys. Res. Lett., 32, L03111
Lu, Q. M., Wu, C. S., & Wang, S. 2006, ApJ, 638, 1169
Nakariakov, V., Ofman, L., Deluca, E. E., Roberts, N., & Davilla, J. M. 1999, Science, 285, 862
Smith, E. J., Balogh, A., Neugebauer, M., & McComas, D. 1995, Geophys. Res. Lett., 22, 3381
Ulrich, R. K. 1996, ApJ, 465, 436
Wang, C. B., Wu, C. S., & Yoon, P. H. 2006, Phys. Rev. Lett., 96, 125001
Wu, C. S., Yoon, P. H., & Chao, J. K. 1997, Phys. Plasmas, 4, 856