Physical Process for the Pick-Up of Minor Ions by Low-Frequency Alfvén Waves

2013 Chinese Phys. Lett. 30 055201

(http://iopscience.iop.org/0256-307X/30/5/055201)

CHIN. PHYS. LETT. Vol. 30, No. 5 (2013) 055201

Physical Process for the Pick-Up of Minor Ions by Low-Frequency Alfvén Waves *

WANG Chuan-Bing(王传兵)[1**], WEI Jing-Dong(韦京东)[1], WANG Bin(王斌)[2], WANG Shui(王水)[1]
[1]*CAS Key Lab of Geospace Environment, Department of Geophysics and Planetary Science,*
University of Science and Technology of China, Hefei 230026
[2]*Beijing Institute of Tracing and Telecommunications Technology of China, Beijing 100094*

(Received 5 January 2013)

We study the physical process for the pick-up of minor ions by obliquely propagating low-frequency Alfvén waves. It is demonstrated that minor ions can be picked up by the intrinsic low-frequency Alfvén waves observed in the solar wind. When the wave amplitude exceeds the threshold condition for stochasticity, a minor ion can gain a high magnetic moment through the stochastic heating process. Then, the ion with a large magnetic moment can be trapped in the magnetic mirror-like field structures formed by the large-amplitude low-frequency Alfvén waves in the wave frame. As a result, the ion is picked up by the Alfvén waves.

PACS: *52.35.−g*, *96.50.−e*, *96.50.Ci* DOI: 10.1088/0256-307X/30/5/055201

Observations show that intrinsic large-amplitude Alfvén waves exist pervasively in the interplanetary medium.[1,2] The wave magnetic field amplitude is often comparable to the ambient magnetic field intensity. Alfvén wave-like fluctuations have also been measured remotely in the chromosphere[3] and corona.[4] It is generally believed that Alfvén waves play an important role in the preferential heating and acceleration of minor ions in the solar corona and wind. Typically, minor ions have much higher perpendicular temperature anisotropy in the solar corona. For example, it is found that O^{5+} have a strong temperature anisotropy ($T_\perp/T_\parallel > 10$).[5,6] The flow speed of O^{5+} ions can exceed that of protons by as much as 200–300 km/s.[7,8] Satellite in situ observations in the solar wind indicate that minor ions have mass-proportional kinetic temperatures, and also flow faster than protons with a relative speed equal to or less than the local Alfvén speed.[9−12]

A number of theories that involve wave-particle interactions between Alfvén waves and ions in the solar corona and wind have been put forward.[13−17] Most of these theories are based on the resonant wave-particle interactions. However, there are theoretical difficulties with the application of the ion cyclotron-resonant mechanism, and its role is not yet fully understood.[18]

Recently, the low-frequency Alfvén waves and kinetic Alfvén waves have attracted much attention. Several different theoretical approaches, which are not based on the cyclotron resonant interaction, have been suggested. Firstly, it has been argued that under low-beta plasma conditions, due to the pitch-angle scattering of ions, the ion temperature anisotropy of ions could be caused by Alfvénic fluctuations with frequencies well below the local ion-cyclotron frequency.[19−22] The energy gain for the ions is proportional to the wave energy density δB_w^2, where δB_w is the average magnetic field wave amplitude. The second approach imposes a somewhat different concept of heating by emphasizing the stochasticity of particle motion.[23−33] The basic idea is that when the wave amplitude exceeds a certain threshold value, the motion of the particle may change from regular to stochastic due to the high-order nonlinear resonance or the kinetic effect of the finite ion lamor-radius.

In a previous study,[29] we discussed the stochastic heating and acceleration of minor ions by low-frequency obliquely propagating Alfvén waves in the solar wind. It was found that when the wave amplitude exceeds some threshold condition for stochasticity, the time-asymptotic kinetic temperature associated with the minor ions becomes independent of the wave amplitude. In the course of the heating process, the minor ions gain a net average parallel speed approximately equal to the Alfvén speed in the plasma frame. The physical mechanism for the asymptotically independent heating is the pick-up process that involves the formation of the spherical shell velocity distribution function due to the pitch-angle scattering. However, the physical process for the pick-up of minor ions by obliquely propagating low-frequency Alfvén waves is not discussed in detail.

In this Letter, we investigate the physical processes of how minor ions can be picked up by low-frequency Alfvén waves. We assume that intrinsic Alfvén waves pervade in the solar wind, which propagate outward from the sun. How these waves are produced and propagate in the solar corona and solar wind is not discussed in this study. The presence of minor ions does not have any significant impact on the intrinsic turbulence because the minor ion abundance is small. Consequently, we adopt the test particle simulations for simplicity. Let the ambient magnetic field $\boldsymbol{B}_0$ be in the z-direction. We consider linearly polarized in-

---

*Supported by the National Natural Science Foundation of China under Grant Nos 41174123, 40931053 and 41121003, the Chinese Academy of Sciences under Grant Nos KZCX2-YW-QN512 and KZZD-EW-01, and the Fundamental Research Funds for the Central Universities under Grant No WK2080000031.

**Corresponding author. Email: cbwang@ustc.edu.cn

coherent Alfvén waves propagating obliquely with respect to the ambient magnetic field. In the reference frame moving with the wave speed, the wave magnetic field vector can thus be expressed as

$$\delta \boldsymbol{B}_w = \sum_{j=1}^{N} B_j(t) \cos\psi_j \boldsymbol{i}_y, \tag{1}$$

where $\psi_j = k_x x + k_z z + \varphi_j$ and $\theta = \arctan(k_x/k_z)$ is the wave propagation angle with respect to the ambient magnetic field line; k_x and k_z are wave numbers perpendicular and parallel to the ambient magnetic field; φ_j and B_j are the random phase constant and amplitude for mode j; $\omega = k_z V_\mathrm{A}$ is the wave frequency; V_A is the Alfvén speed; and $\boldsymbol{i}_y$ is a unit vector along the y-direction. Without loss of generality, we consider the wave propagation angle $\theta = \pi/4$ for all wave modes in the following calculations. The particle dynamics are governed by

$$m_i \frac{d\boldsymbol{v}}{dt} = q_i \boldsymbol{v} \times (\boldsymbol{B}_0 + \delta\boldsymbol{B}_w), \quad \frac{d\boldsymbol{r}}{dt} = \boldsymbol{v}, \tag{2}$$

where m_i and q_i are the mass and electric charge of each minor ion, respectively. The equations of motion are solved with the Boris algorithm, where the kinetic energy of the particle is conserved in the calculation over the cyclotron motion. We discretize the Alfvén wave spectrum as follows: $\omega_j = \omega_1 + (j-1)\Delta\omega$ $(j = 1, 2, \ldots, N)$, where $\Delta\omega = (\omega_N - \omega_1)/(N-1)$, and N is the total number of wave modes. The amplitude of each wave mode satisfies a power-law relation with a spectral index $-\alpha$, $B_j^2 \propto \omega_j^{-\alpha}$, and α is chosen to be 5/3. To avoid the strong initial-pitch-angle scattering effect,[34] we also let the amplitude of each wave mode change gradually with time from an initially small value to a finite amplitude such that the wave energy density $\delta B_w^2(t)/B_0^2 = \sum_j B_j^2(t)/2B_0^2 = \varepsilon(t)$, and

$$\varepsilon(t) = \begin{cases} \varepsilon_0 e^{-(t-\tau)^2/(\Delta\tau)^2}, & t < \tau, \\ \varepsilon_0, & t \geq \tau, \end{cases} \tag{3}$$

where ε_0 is the final wave energy density normalized with the ambient magnetic field. We choose $\tau = 200\Omega_\mathrm{p}^{-1}$ and $\Delta\tau = 50\Omega_\mathrm{p}^{-1}$, where $\Omega_\mathrm{p} = eB_0/m_\mathrm{p}c$ is the proton cyclotron frequency.

We are interested in the minor ions in the solar wind. Thus, we adopt O^{5+} as the test particles. The velocity and time are normalized with respect to the Alfvén speed V_A and Ω_p^{-1}, respectively. The time step is $\Omega_\mathrm{p}\Delta t = 0.001$. The total number of test particles is 5000, and these are initially distributed at random during the time interval $\Omega_\mathrm{p} t = [0, 2\pi]$ and along the spatial range $z\Omega_\mathrm{p}/V_\mathrm{A} = [0, 3000]$ and $x\Omega_\mathrm{p}/V_\mathrm{A} = [0, 3000]$. Their initial velocities are assumed to be distributed according to a Maxwellian distribution with thermal speed v_Ti.

In the following, we would like to demonstrate that minor ions can be picked up by low-frequency Alfvén waves. Moreover, the physical process for the pick-up is explained in detail. Three cases are studied in this work. The specific parameters are shown in Table 1.

Table 1. The specific simulation parameters for the three cases studied in this work.

case	$\omega_1/\Omega_\mathrm{p}$	$\omega_N/\Omega_\mathrm{p}$	N	$\beta = v_\mathrm{Ti}^2/v_\mathrm{A}^2$	$\varepsilon_0 = \delta B_w^2/B_0^2$
1	0.05	0.1	31	0.1	0.1
2	0.05	0.1	31	0.1	0.3
3	0.05	0.1	31	0.1	0.5

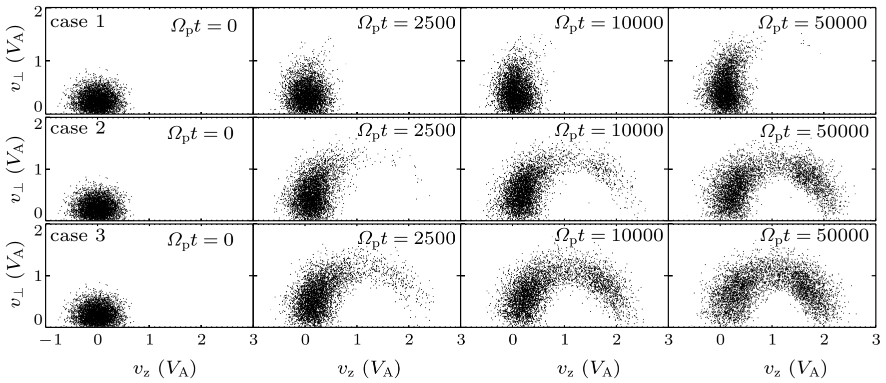

Fig. 1. The velocity scatter-plot of O^{5+} in the v_z–$v_\perp$ phase plane in the plasma frame at different simulation times, where v_z and $v_\perp = (v_x^2 + v_y^2)^{1/2}$ are velocities in the direction parallel and perpendicular to the ambient magnetic field, respectively. The upper, medium and bottom panels are the results for case 1, case 2 and case 3, respectively.

Figure 1 is a velocity scatter-plot of O^{5+} in the v_z versus $v_\perp$ phase plane for case 1 (upper panel), case 2 (medium panel) and case 3 (bottom panel) in the plasma frame at different simulation times. In case 1, very few particles are pitch-angle scattered to the right half-side of the spherical shell at the end of the simulation. Clearly, the wave amplitude does not exceed the threshold value for stochasticity. The increase in the ion kinetic energy in case 1 is mainly due to the non-resonant pseudoheating process discussed in Refs. [19,20]. In case 2, although the wave amplitude satisfies the threshold condition for stochasticity, only part of particles can be pitch-angle scattered to the right half-side of the spherical shell at the end of the simulation. This is because the wave amplitude is not large enough. For case 3, there is strong stochastic heating and acceleration, and O^{5+} can be fully picked up by the waves through forming a spherical shell distribution at the end of the simulation. This spherical shell distribution is the result of ion energy conservation in the wave frame. The center of the spherical shell is located at the wave phase speed, namely, the Alfvén speed V_A.

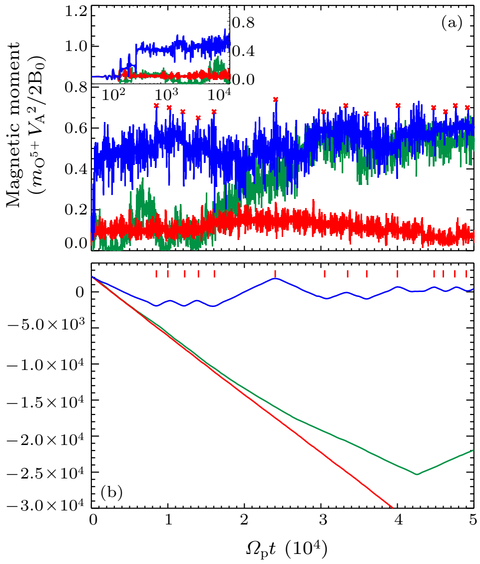

Fig. 2. The variation in magnetic moment (upper panel) and position z (bottom panel) of an ion in the wave frame with simulation time. The red, green and blue lines represent the results of case 1, case 2 and case 3, respectively. Each ion has the same initial velocity and position in all three simulation cases. The small red crosses and short vertical bars indicate the times when the ion is reflected by a large amplitude wave field due to magnetic mirror force for case 3. The small upper-left picture in the upper panel shows the variation in magnetic moment with time in logarithmic scale for the first $10^4 \Omega_p t$ simulation time.

To understand the role that the low-frequency Alfvén waves play during the pick-up process, we track the moving trajectories of individual particles at different times in the three simulation cases.

Figure 2 shows the variations in the magnetic moment and position z of an ion with time in the wave frame for the three simulation cases. The results for cases 1, 2 and 3 are represented by the red, green and blue lines, respectively. Each ion has the same initial velocity and position in all three simulation cases. In Fig. 2, the magnetic moment $\mu = m_{O^{5+}} v_\perp^2/(2|\boldsymbol{B}_t|^2)$ is defined with respect to the local total magnetic field $\boldsymbol{B}_t = \boldsymbol{B}_0 + \delta\boldsymbol{B}_w(z,x)$, where $\delta\boldsymbol{B}_w(z,x)$ is the wave magnetic field at position (z,x). It is found that the ion magnetic moment μ changes greatly with time in both case 2 and 3, while it is nearly constant at different times in case 1. The reason for this is that in case 1 the wave amplitude is not large enough to ensure that any nonlinear stochastic heating process will have a significant effect. The ion magnetic moment μ is almost conserved in case 1. However, in both case 2 and 3, the amplitude of the low-frequency Alfvén waves exceeds the threshold value for stochasticity; the magnetic moment μ of an ion is not conserved due to the stochastic heating process. The magnetic moment μ increases quickly from an initial value of about $0.1 m_{O^{5+}} V_A^2/2B_0$ to the value of about $0.5 m_{O^{5+}} V_A^2/2B_0$ in case 3, as shown in the small picture on the upper-left corner of the upper panel in Fig. 2.

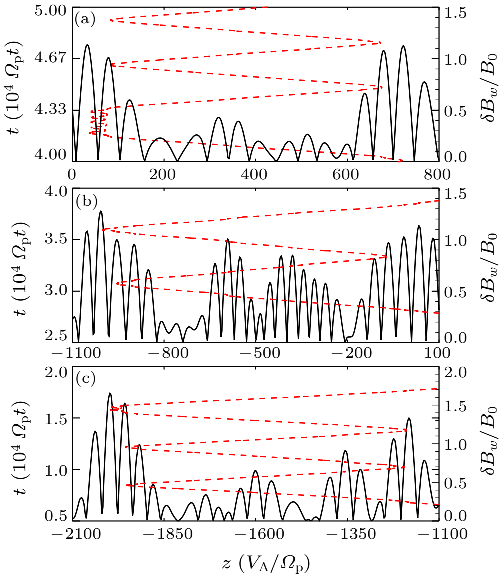

Fig. 3. The red dashed lines show the projected trajectories of an ion along the ambient magnetic field in the wave frame at three selected time intervals in case 3. The solid curves represent the strength of the wave magnetic field experienced by this ion at different positions. This ion is the same ion as shown in Fig. 2. The reflecting time is also indicated by the small red crosses and short vertical bars in Fig. 2.

In Fig. 2, the ion position z decreases monotonously with the increase of time in case 1. This means that the ion is always streaming away along the direction anti-parallel to the ambient magnetic field in the wave frame. On the other hand, the same ion changes, moving from the anti-parallel direction to the parallel direction, and vice versa, one or more times in cases 2 and 3. This means that this ion is trapped in the wave field. In other words, this ion is picked up by waves in these cases. The physical reason for this is that the ion with a relatively large μ can be intermittently bounced backward and forward, or from the left-side (right-side) to the right-side (left-side) of the spherical shell in Fig. 1, by the large amplitude wave field due to magnetic mirror force in cases 2 and 3.

This reflecting and trapping process can be seen more clearly in Fig. 3, which illustrates the trajectory of this same ion along the z-axis (red dashed line) and the absolute value of the wave magnetic field strength (solid line) at three time intervals in case 3.

In the wave frame, the amplitude of the turbulent low-frequency Alfvén waves changes slowly in space. The wave field strength is weak in some areas, while it can have relatively large values at other positions. Thus, a number of magnetic mirror-like field structures can be formed in the wave frame. Under some conditions, the ion can be bounced back at the mirror point, or can even be trapped by these mirror-like wave field structures, as shown in Fig. 3. It is found that this ion is reflected or bounced back five times in the region $z \approx [-2100, -1100]V_{\rm A}/\varOmega_{\rm p}$ (bottom panel in Fig. 3), three times at the position $z \approx [-1100, 100]V_{\rm A}/\varOmega_{\rm p}$ (medium panel), and more than 10 times in the region $z \approx [0, 800]V_{\rm A}/\varOmega_{\rm p}$ (upper panel). This ion experiences a large amplitude wave magnetic field each time the ion is bounced back. The time when this ion is reflected is also indicated by the red crosses and short vertical bars in Fig. 2 for case 3. One can see from Fig. 2 that the magnetic moments μ of the ion have high values, generally greater than $0.6m_{O^{5+}}V_{\rm A}^2/2B_0$, when the motion of the ion is bounced back or trapped by mirror-like field structures. This is not surprising. The higher the magnetic moment, the larger the velocity component perpendicular to the local magnetic field, and the smaller the parallel velocity component. An ion with small parallel velocity can be bounced back more easily when the ion moves in a region with a gradually increasing magnetic field strength.

In summary, we have demonstrated that minor ions may be picked up by obliquely propagating low-frequency Alfvén waves as long as the wave amplitude exceeds the threshold condition for stochasticity, which pervade intrinsically in the solar corona and interplanetary space. The basic physics for the pick-up process can be described as follows. A minor ion can obtain a high magnetic moment through the stochastic heating process. Then, an ion with a large magnetic moment can be intermittently bounced backward and forward or trapped by magnetic mirror-like field structures formed by the large-amplitude low-frequency Alfvén waves. When an ion is trapped in the wave field, it will co-move with the waves. In other words, the ion is picked up by these waves. When minor ions are fully picked up by Alfven waves, they will have mass-proportional kinetic temperatures and flow faster than protons with a relative speed roughly equal to the Alfven speed.[29,30] This process is significant for us to understand the observed kinetic properties of minor ions in the solar corona and wind, namely, they are hotter and flow faster than protons with a relative speed equal to or less than the local Alfvén speed.[10−12]

Finally, it is worth noting that large-amplitude low-frequency Alfven waves may decay into daughter waves in a multiple-wave interaction process.[35−37] Observations also show that there is a spectrum of turbulent waves in the solar wind.[38,39] We believe that the pick-up process discussed here is still workable for minor ions in the solar wind with a broader spectrum of waves, because most of the observed wave energy is occupied by waves with a frequency far below the ion gyro-frequency. Waves with a frequency near the ion gyro-frequency will be helpful in randomizing the ion orbit and can increase the ion magnetic moment. However, the minor ion is still trapped and picked up by the magnetic mirror-like field structures formed by low-frequency waves.

References

[1] Belcher J W and Davis L J 1971 *J. Geophys. Res.* **76** 3534
[2] Smith C W, Vasquez B J and Hamilton K 2006 *J. Geophys. Res.* **111** A09111
[3] Pontieu B et al 2007 *Science* **318** 1574
[4] Tomczyk S et al 2007 *Science* **317** 1192
[5] Li X, Habbal S R, Kohl J L and Noci G 1998 *Astrophys. J. Lett.* **501** L133
[6] Cranmer S R et al 1999 *Astrophys. J.* **511** 481
[7] Kohl J L et al 1997 *Sol. Phys.* **175** 613
[8] Kohl J L et al 1998 *Astrophys. J. Lett.* **501** L127
[9] Marsch E et al 1981 *J. Geophys. Res.* **86** 9199
[10] Marsch E et al 1982 *J. Geophys. Res.* **87** 35
[11] Von Steiger R, Geiss J, Gloeckler G and Galvin A B 1995 *Space Sci. Rev.* **72** 71
[12] Von Steiger R and Zurbuchen T H 2006 *Geophys. Res. Lett.* **33** L09103
[13] Cranmer S R 2001 *J. Geophys. Res.* **106** 24937
[14] Tu C Y and Marsch E 2001 *J. Geophys. Res.* **106** 8233
[15] Gary S P, L Yin, Winske D and Ofman L 2001 *J. Geophys. Res.* **106** 10715
[16] Vocks C and Marsch E 2002 *Astrophys. J.* **568** 1030
[17] Li B et al 2004 *J. Geophys. Res.* **109** A07103
[18] Ofman L 2010 *Sol. Phys.* **7** 4
[19] Wang C B, Wu C S and Yoon P H 2006 *Phys. Rev. Lett.* **96** 125001
[20] Wang C B and Wu C S 2009 *Phys. Plasmas* **16** 020703
[21] Wu C S and Yoon P H 2007 *Phys. Rev. Lett.* **99** 075001
[22] Li X, Lu Q M and Li B 2007 *Astrophys. J.* **661** L105
[23] Lin Y and Lee L C 1991 *Geophys. Res. Lett.* **18** 1615
[24] Chen L, Lin Z and White R B 2001 *Phys. Plasmas* **8** 4713
[25] Lv X, Li Y and Wang S 2007 *Chin. Phys. Lett.* **24** 2010
[26] White R B, Chen L and Lin Z 2002 *Phys. Plasmas* **9** 1890
[27] Guo Z, Crabtree C and Chen L 2008 *Phys. Plasmas* **15** 032311
[28] Lu Q M and Chen L 2009 *Astrophys. J.* **704** 743
[29] Wang Bin, C B Wang, Yoon P H and Wu C S 2011 *Geophys. Res. Lett.* **38** L10103
[30] Wang Bin 2012 *PhD Dissertation (Hefei: University of Science and Technology of China)* (in Chinese)
[31] Wu D J and Yang L 2006 *Astron. Astrophys.* **452** L7
[32] Yang L and Wu D J 2006 *Chin. Phys. Lett.* **23** 2155
[33] Chandran B D et al 2010 *Astrophys. J.* **720** 503
[34] Wang Bin and Wang C B 2009 *Phys. Plasmas* **16** 082902
[35] Galeev A A and Oraevskii V N 1963 *Sov. Phys. Dokl.* **7** 988
[36] Araneda J A, Marsch E and Vinas A F 2007 *J. Geophys. Res.* **112**
[37] Verscharen D et al 2012 *Phys. Rev.* E **86** 027401
[38] Tu C Y and Marsch E 1995 *Space Sci. Rev.* **73** 1
[39] Bourouaine S, Marsch E and Neubauer F M 2011 *Astron. Astrophys.* **536** A39