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A KINETIC ALFVÉN WAVE AND THE PROTON DISTRIBUTION FUNCTION IN THE FAST SOLAR WIND

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ABSTRACT

Using one-dimensional test particle simulations, the effect of a kinetic Alfvén wave on the velocity distribution function (VDF) of protons in the collisionless solar wind is investigated. We first use linear Vlasov theory to numerically obtain the property of a kinetic Alfvén wave (the wave propagates in the direction almost perpendicular to the background magnetic field). We then numerically simulate how the wave will shape the proton VDF. It is found that Landau resonance may be able to generate two components in the initially Maxwellian proton VDF: a tenuous beam component along the direction of the background magnetic field and a core component. The streaming speed of the beam relative to the core proton component is about 1.2–1.3 Alfvén speed.

Key words: solar wind – waves

1. INTRODUCTION

The quest for possible heating and the acceleration mechanisms of the solar wind have been an active research field for decades (see review papers: Hollweg & Isernberg 2002; Marsch 2005; Cranmer 2009). Beyond several solar radii, the solar wind proton gas is basically Coulomb collisionless. Indeed, in situ measurements of protons in the fast solar wind have shown that proton velocity distribution functions (VDFs) have distinctive features of collisionless plasmas: in the fast solar wind, the proton temperature in the direction perpendicular to the background interplanetary magnetic field is higher than that in the parallel direction. This suggests that a mechanism that continuously heats solar wind protons as the solar wind expands in interplanetary space is needed. Double beams along the background magnetic field lines also frequently occurred in the measured proton VDFs (Feldman et al. 1973, 1993; Marsch et al. 1982). It is also common that double-beam proton velocity distributions are not prominent. Instead, the proton VDFs are elongated along the background magnetic field in the anti-sunward direction (Marsch et al. 1982).

Several physical processes have been suggested to account for the generation of the proton beam. These mechanisms include Coulomb collisions in the lower corona (Livi & Marsch 1987), jets produced by magnetic reconnections that are injected into the solar wind at the base of expanding coronal loops (Feldman et al. 1996), the combined effect of collisions and quasi-linear resonant heating (Tam & Chang 1999), or quasi-linear diffusion caused by both left- and right-handed cyclotron waves in the second dispersion branch due to the presence of fully ionized helium (Tu et al. 2002). More recently, Araneda et al. (2008) found that a large amplitude circularly polarized dispersive Alfvén-cyclotron wave with frequency at 32% of the proton gyrofrequency may generate ion acoustic waves at the condition that the electron temperature be over seven times the proton temperature and that the electric field of the ion acoustic waves be able to produce a secondary proton beam.

At sufficiently large θ (the angle between wave vector $\mathbf{k}$ and background magnetic field $\mathbf{B}_0$) and smaller scales ($k_\perp v_p/\Omega_p \sim 1$, where v_p is the proton thermal speed and Ω_p is the proton gyrofrequency), obliquely propagating shear Alfvén waves are often called kinetic Alfvén waves (Hollweg 1999, and references therein). Arguments that kinetic Alfveń waves are present in the solar wind turbulence have been based upon both in situ measurements (Leamon et al. 1998; Bale et al. 2005) and numerical simulations (Howes et al. 2008). In general, the observed inertial range magnetic turbulence is strongly anisotropic: for a given wave number k, magnetic fluctuation energy is much stronger at quasi-perpendicular propagation ($k_\perp \gg k_\parallel$) than it is at quasi-parallel propagation ($k_\perp \ll k_\parallel$) (Matthaeus et al. 1990; Bieber et al. 1996; Horbury et al. 2005; Dasso et al. 2005). Under compressible MHD turbulence theory, nonlinear wave/wave interactions can transfer wave energy to high-frequency Alfvén waves, although the interactions transfer energy to high-frequency fast waves more efficiently (Chandran 2005).

In this Letter, we explore the role of kinetic Alfvén waves in shaping the VDFs of solar wind protons. We first use Vlasov linear wave theory to find the property of a kinetic Alfvén wave. The electromagnetic fields of the wave are then used to act on protons. A test particle simulation is used to compute the dynamics of individual protons. It is found that via Landau resonance a kinetic Alfvén wave is able to significantly influence the VDF of protons: the VDFs of protons become elongated along the background magnetic field, and double-beam VDFs can be formed.

We denote electrons by subscript e and protons by p. Subscripts $\perp$ and $\parallel$ denote directions parallel and perpendicular to the background magnetic field $\mathbf{B}_0$. For the jth species, we define $\beta_j = 8\pi n_j k_B T_{\parallel j}/B_0^2$, the cyclotron frequency, $\Omega_j = e_j B_0/m_j c$, and the thermal speed, $v_j = \sqrt{2k_B T_{\parallel j}/m_j}$. The Alfveń speed is $v_A = B_0/\sqrt{4\pi n_p m_p}$. The complex angular frequency is $\omega = \omega_r + i\omega_i$, the Landau resonance factor of the jth species is $\zeta_j = \omega/k_\parallel v_j$, and the cyclotron resonance factors of the jth species are $\zeta_j^\pm = (\omega \pm \Omega_j)/k_\parallel v_j$.

2. LINEAR THEORY

Based on Vlasov theory, the linear property of kinetic Alfvén waves has been explored by many authors (e.g., Li & Habbal 2001; Gary & Nishimura 2004; Gary & Borovsky 2004, 2008). Following these studies, we define the background magnetic

Table 1
Parameters of Perturbations[a]

	x	y	z
$\delta E_\alpha/\lvert\delta\mathbf{B}\rvert_0$	1	0.0067	0.003
$\phi_{E\alpha}$	0	86°.7	166°.9
$((\delta u_\alpha)_0/v_A)/(\lvert\delta\mathbf{B}\rvert_0/B_0)$	0.0091	0.812	0.316
$\phi_{u\alpha}$	−88°.7	180°.1	166°.9

Note. [a] $\omega_r/\Omega_p = 0.01937$, $\theta = 89°$.

field $\mathbf{B}_0$ to be along the z-coordinate. The wave vector $\mathbf{k}$ is in the xz plane, and the angle between $\mathbf{k}$ and $\mathbf{B}_0$ is θ. Linear Vlasov theory can predict the dispersion relation of kinetic Alfvén waves and the property of the wave. We use a linear Vlasov plasma wave solver (Li & Habbal 2001) to find the dispersion relation of kinetic Alfvén waves. At $\beta_e = \beta_p = 0.5$, $kv_A/\Omega_p = 1$, and $\theta = 89°$ ($k_\perp/k_\parallel \approx 57.3$) it yields $\omega/\Omega_p = 0.01937 - i2.65\times 10^{-4}$. The real part of the Landau resonance factor is $\zeta_p = 1.57$ and that of the proton cyclotron resonance factor is $\zeta_p^+ = 79.5$. Protons are weakly Landau resonant with the wave and not in cyclotron resonance with the wave. We thus expect that the wave can scatter the protons via Landau resonance. The plasma beta values are those of the fast solar wind at heliocentric distances 100–200 solar radii (Li et al. 1999).

We write the electric field and the perturbed proton flow speed of the wave as

$$\delta\mathbf{E}(x',t) = \sum_{\alpha=x,y,z} \mathbf{e}_\alpha(\delta E_\alpha)\cos(kx' - \omega_r t + \phi_{E\alpha}), \qquad (1)$$

$$\delta\mathbf{u}(x',t) = \sum_{\alpha=x,y,z} \mathbf{e}_\alpha(\delta u_\alpha)\cos(kx' - \omega_r t + \phi_{u\alpha}), \qquad (2)$$

where $\mathbf{e}_\alpha$ ($\alpha = x, y, z$) are unit vectors in Cartesian coordinates. The $\delta\mathbf{E}$ and the perturbed magnetic field $\delta\mathbf{B}$ are related by

$$\delta\mathbf{B}(x',t) = \mathbf{k}\times\delta\mathbf{E}(x',t)/\omega, \qquad (3)$$

and $|\delta B|^2/B_0^2 = 0.09$. x' is defined as $x' = x\sin\theta + z\cos\theta$. Some relevant parameters of the wave are displayed in Table 1.

3. MODEL

The motion of protons is governed by equation

$$\begin{cases} m_p \frac{d\mathbf{v}}{dt} = e[\delta\mathbf{E} + \mathbf{v}\times(B_0\mathbf{e}_z + \delta\mathbf{B})], \\ \frac{dx'}{dt} = v_{x'},\ v_{x'} = v_x\sin\theta + v_z\cos\theta. \end{cases} \qquad (4)$$

We conduct one-dimensional test particle simulations along x' by calculating the full dynamics of protons (Equation (4)) in the electromagnetic field of a kinetic Alfvén wave given in Table 1 and Equations (1) and (3). The perturbed flow speed in Equation (2) and Table 1 is also introduced to the system at the start ($t = 0$) of the simulations. The wave properties described in Equations (1)–(3) and given in Table 1 are computed by our Vlasov code. The disturbed plasma flow speed in Equation (2) is often refered to as wave sloshing motions in the literature. In the simulation, the damping of the wave is neglected. It is assumed that a turbulence cascade may be able to strengthen kinetic Alfvén waves. The one-dimensional test particle simulation code is the same as that used by Li et al. (2007) and Lu & Li (2007), but modified to fit the purpose of simulating the role of an obliquely propagating wave. The accuracy of the code is robust. We use periodic boundary conditions and a time step $\Delta t = 0.01\Omega_p^{-1}$. A total of 200,000 particles with the initial Maxwellian velocity distribution were evenly distributed in a region with length $200v_A\Omega_p^{-1}$ (200 cells) at the start of the simulation ($\Omega_p t = 0$).

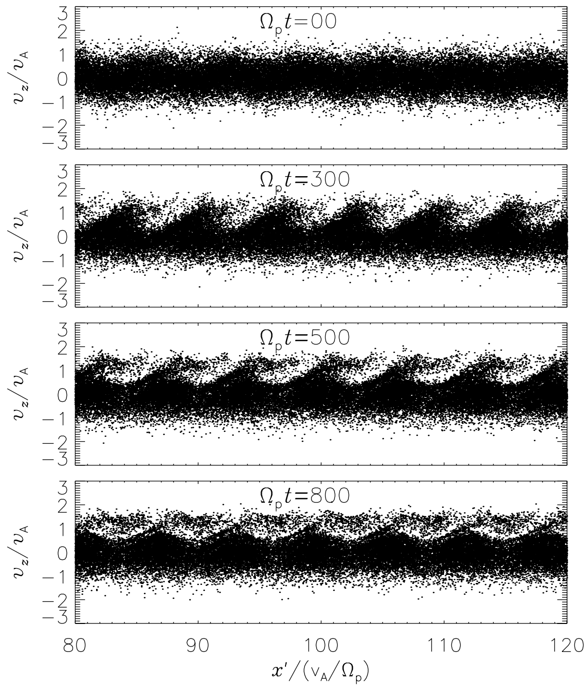

Figure 1. Proton phase space at $\Omega_p t = 0$, 300, 500, and 800.

4. RESULTS

We now discuss our simulation results. To display the scattering of protons by a kinetic Alfvén wave described in Section 2, Figure 1 shows a segment of the scatter plots of v_z with $x'/(v_A\Omega_p^{-1})$ between 80 and 120 at $\Omega_p t = 0$, 300, 500, and 800. At $\Omega_p t = 0$, the effect of small fluctuation of δu_z can be seen. Dramatic changes are already obvious at $\Omega_p t = 300$: v_z overshoots at the wave crest in the direction that the kinetic Alfvén wave propagates (positive x' direction). The overshoot occurs around $v_z \sim 1.2\,v_A$. As shown in Table 1, the phase speed of the wave is $\omega_r/k_\parallel = 0.01937/\cos(89°)v_A \simeq 1.11\,v_A$. Hence, the overshoot is due to Landau resonance between particles with v_z around 1.2 v_A and the wave. In the wave frame, these particles may be trapped in the wave potential trough, and the VDF could become flat in the vicinity of the phase speed of the kinetic wave. The overshoot continues at $\Omega_p t = 500$ and 800. At these two instants, a substantial fraction of the protons in the proton VDF are lifted to a higher v_z. Since the wave frequency is very low compared with the proton gyrofrequency, ion cyclotron resonance is absent. Landau resonance is the only resonant wave/particle interaction process possible in the system. Landau resonance must be responsible for the apparent acceleration of protons along the background magnetic field direction.

Spatially averaged proton VDFs in the ($v_\parallel$, v_y) plane at $\Omega t = 300$, 500, 800, and 1000 are shown in Figure 2. Since initially protons' VDFs are Maxwellian, the departure of the VDF from Maxwellian at $\Omega_p t = 300$ is due to the kinetic Alfvén wave that is introduced. From $\Omega_p t = 300$ to $\Omega_p t = 500$, protons' VDFs are elongated in the parallel direction. However,

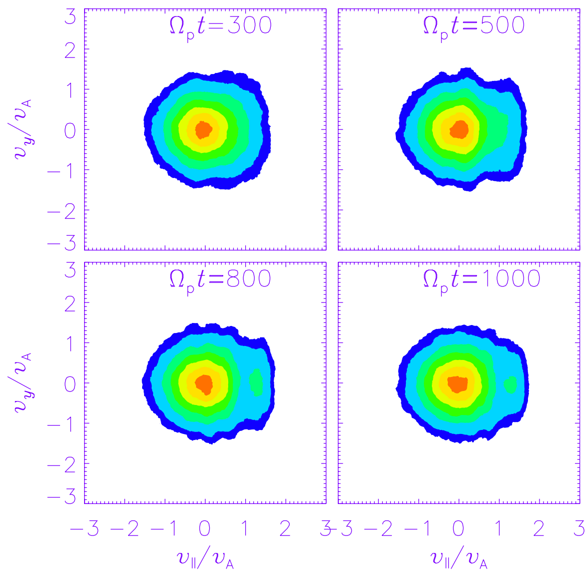

Figure 2. Spatial averaged proton velocity distributions in the ($v_\parallel$, v_y) plane at $\Omega_p t = 300$, 500, 800, and 1000. The color coding of the contour lines corresponds, respectively, to 90% (red), 70% (dark yellow), 50% (yellow), 30% (dark green), 15% (green), 5% (light blue), and 2% (blue) of the maximum, with a final beam density of about 6%.

the elongation mainly occurs at $v_\parallel/v_A > 0$. The elongation of the VDF eventually becomes so pronounced that a secondary beam component is formed as shown at $\Omega_p t = 800$ and $\Omega_p t = 1000$, leaving behind a core proton component.

It is clear from Figure 2 that the kinetic Alfvén wave does not produce heating in the direction perpendicular to $\mathbf{B}_0$. This is due to the low frequency of the wave. On the other hand, in situ measurements found that the core proton component has a higher perpendicular than parallel temperature in high-speed solar wind flows (Marsch et al. 1982). Other mechanisms, for example, parallel propagating ion cyclotron waves at higher frequency (see review of Hollweg & Isenberg 2002), are needed for the observed perpendicular heating.

5. DISCUSSION AND CONCLUSIONS

Using one-dimensional test particle simulations, we have demonstrated that a nearly perpendicular propagating kinetic Alfvén wave is able to generate a secondary proton beam in collisionless plasmas such as the solar wind. The proton beam occurs in the direction along the background magnetic field $\mathbf{B}_0$.

Although the kinetic Alfvén wave propagates in the direction almost perpendicular to the background magnetic field $\mathbf{B}_0$, ($\theta = 89^\circ$ in this Letter), it is well known that the group speed of a kinetic Alfvén wave is in the direction either parallel or anti-parallel to $\mathbf{B}_0$. In the case that $\theta = 89^\circ$, the group speed of the wave is parallel to $\mathbf{B}_0$. If we assume that the kinetic Alfvén wave originates from the Sun or the near-Sun region of the solar wind, the wave is then able to produce a secondary beam component in the anti-Sun direction, which is observed by in situ measurements (Marsch et al. 1982). Figure 2 shows that the relative streaming between the beam and core components is about 1.2–1.3 v_A (just slightly higher than the phase speed of the wave 1.11 v_A), in agreement with observations (Goldstein et al. 2000).

Using 2.5-dimensional particle-in-cell simulations, Gary & Nishimura (2004) found that kinetic Alfvén waves are able to produce an electron beam. In their study, the density of the produced electron beam is comparable to the core component. However, they did not comment on the effect of the wave on the proton VDF. Full particle simulations are computationally expensive and their calculations are terminated at $\Omega_p t = 50$. At this short time scale, the effect of the wave on the proton VDF is insignificant. Our one-dimensional test particle simulations are computationally much less expensive, and we are able to compute to a much longer time scale.

Our present study has several obvious limitations. First, we have adopted one-dimensional test particle simulations. The feedback of the particles including both protons and electrons to the kinetic Alfvén wave is not accounted for. Second, we have adopted the property of a kinetic Alfvén wave from linear Vlasov theory. However, to illustrate the effect of the wave, the amplitude of the kinetic Alfvén wave is finite and the nonlinearity of the wave may not be negligible. And finally, at near perpendicular propagation, the interaction between particles and kinetic Alfvén waves is at least two dimensional in nature. Despite these limitations, it is very likely that the results of the current one-dimensional test particle simulation have captured the most important aspect of the proton/kinetic Alfvén wave interaction. This is supported by a new paper by Osmane et al. (2010), which became available in the public domain after our manuscript had been submitted. Using essentially the same approach as ours, Osmane et al. (2010) reached the similar conclusion that obliquely propagating Alfvén waves may be able to generate a fast proton beam in the fast solar wind. They adopted a relatively high plasma beta (2 instead of 0.5 in our case), a higher wave frequency, and a moderate wave propagation angle 40° ($k_\perp$ and $k_\parallel$ are comparable). Another difference is that we use Vlasov theory to compute the property of the kinetic Alfvén wave while they computed the wave property using fluid theory.

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