Ion cyclotron waves, instabilities and solar wind heating

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Abstract. The effect of alpha particles on the dispersion relation of ion cyclotron waves and its influence on the heating of the solar wind plasma are investigated. The presence of alpha particles can dramatically change the dispersion relation of ion cyclotron waves, and significantly influence the way that ion cyclotron waves heat the solar wind plasma. We find that a spectrum of ion cyclotron waves affects the thermal anisotropy of the solar wind protons and other ions differently in interplanetary space: When alpha particles have a speed $u_\alpha > 0.5 v_A$, and both protons and alpha particles have a thermal anisotropy $T_\perp / T_\| > 1$, ion cyclotron waves heat protons in the direction perpendicular to the magnetic field, cool them in the parallel direction, and exert the opposite effect on alpha particles.

Keywords: ion cyclotron resonance, solar wind

1. Introduction

Four decades after Parker (1958) predicted the existence of the solar wind which was verified a few years later by spacecraft in situ measurements (Snyder and Neugebauer, 1964), the solar wind heating and

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acceleration mechanism continues to elude us and excite our imagination. In situ measurements have shown that the solar wind minor ions not only flow faster than the major ions – protons, but they are preferentially heated as well (e.g., Marsch et al., 1982a,b; Bochsler, Geiss, and Joos, 1985; von Steiger et al., 1995).

The interest in ion-cyclotron resonance (e.g., Hollweg and Turner, 1978; Isenberg, 1984a, Marsch, Goertz, and Richter, 1982) has been recently renewed (Cranmer, Field, and Kohl, 1999; Hollweg, 1999; Hu and Habbal, 1999; Li et al., 1999a, 1999b) by the ultraviolet spectral line observations from UVCS on SOHO indicating larger ion than proton temperatures and implying large temperature anisotropies for protons and minor ions in the inner corona (e.g., Kohl et al., 1998, Li et al., 1998; Cranmer et al., 1999). UVCS observations have shown that oxygen ions O^{+5} have extraordinary perpendicular temperatures (Kohl et al., 1997). By recognizing the importance of the pumping by the second C II line in the interpretation of the UVCS observations, Li et al. (1998) concluded that not only do the oxygen ions flow at a speed around 400 km/s at 3 solar radii and faster than protons, but a large temperature anisotropy exists at the same distance as well (see also, Dodero et al., 1998).

In the past, studies of ion cyclotron resonance in the solar wind either ignored the possible effect of alpha particles on the dispersion relation (Dusenbery and Hollweg, 1981; Marsch, Goertz, and Richter, 1982) or used a simplified dispersion relation (Isenberg and Hollweg, 1983; Isenberg, 1984a). The influence of alpha particles and other minor ions on the dispersion relation of ion cyclotron waves was extensively studied in the past both by solving the dispersion relation and by computer simulation experiments (see review by Cuperman, 1981). The inclusion of minor ions in the solar wind plasma can generate a gap in the dispersion relation of the ion cyclotron waves. The width of the gap is determined by the relative abundance, the charge and the mass of the minor ions (Cuperman, Gomberoff and Sternlieb, 1975). For typical abundances of alpha particles observed in the fast solar wind, the effect of alpha particles on the dispersion relation of ion cyclotron waves was found to be significant (Isenberg, 1984b; Gomberoff, Gratton, and Gravi, 1996). Recently, Hu and Habbal (1999) found that the dispersive effect imposed by the alpha particles has a significant influence on the preferential heating and acceleration by ion cyclotron waves. However, only the cold plasma dispersion relation was adopted in that study, and no temperature anisotropy of the ions was included.

In this paper, we investigate how the warm plasma dispersion relation of ion cyclotron waves affects the heating of the solar wind protons and alpha particles. We will present how ion cyclotron waves, if they are responsible for the solar wind heating and acceleration, influence the temperature anisotropy of different solar wind species.

2. Models

The dispersion relation for parallel propagating ion cyclotron waves in a multicomponent plasma, with the assumption of bi-Maxwellian distribution functions for all plasma components, can be written as (e.g., Stix, 1992)

$$D = \frac{k_{\|}^2 c^2}{\omega^2} - 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \left[\frac{(\omega - k_{\|} u)\Gamma \pm \Omega(\Gamma - 1)}{k_{\|} w_{\|}} \right.$$
$$\left. \times Z_0 \left(\frac{\omega - k_{\|} u \pm \Omega}{k_{\|} w_{\|}} \right) + \Gamma - 1 \right] = 0, \qquad (1)$$

where $k_{\|}$ and ω are the parallel wave number and frequency, respectively. The s under the summation sign refers to a given species, $\Omega_s = q_s B_0 / m_s c$ is the gyro-frequency, where q_s is the electric charge, B_0 is the background magnetic field and c is the speed of light, $\Gamma_s = T_{s\perp}/T_{s\|}$ is the temperature anisotropy of species s, and Z_0 is the plasma dispersion function (Fried and Conte 1961). Both Ω_s and q_s are algebraic quantities. The plasma frequency of species s is $\omega_{ps} = 4\pi n_s q_s^2 / m_s$, its drift velocity is u_s, and its parallel thermal velocity is defined as $w_{s\|} = \sqrt{2 k_B T_{s\|}/m_s}$, where k_B is the Boltzmann constant. The + and

$-$ signs in front of Ω in Equation (1) denote the right- and left-hand polarized ion cyclotron waves. In this paper, only the left-hand parallel propagating ion cyclotron waves are investigated.

With the assumption of charge neutrality, the electron density n_e is equal to $\sum_s q_s n_s/|q_e|$, where n_s is the number density of any species excluding electrons. Zero current is also assumed so that $\sum_s n_s q_s u_s = 0$. Electrons are assumed to be isotropic and T_e is equal to $T_{p\|}$. The wave number $k_\|$ is assumed to be real, so the wave frequency ω can be written as $\omega = \omega_r + i\gamma$, where ω_r and γ are the real and imaginary components respectively. Depending on its sign, γ is the damping (if negative) or growth (if positive) rate of the waves.

We calculate the plasma dispersion function Z_0 and solve the dispersion relation Equation (1) numerically for a plasma containing electrons, protons and alpha particles, i.e. $s = e,\ p,\ \alpha$. The generated Z_0 is at least as accurate as the values given by Fried and Conte (1961). In our calculations, v_A^2/c^2 is assumed to be small and is ignored.

In the solar wind, power spectra of magnetic field fluctuations, most likely of Alfvénic nature, are typically of the form

$$P(k_\|) \propto k_\|^{-\eta} \tag{2}$$

where η is the spectral index. Since observations yield $1.4 \leq \eta \leq 2.0$ (Behannon, 1978; Bavassano et al., 1982), most of the power in the

Alfvénic fluctuations is in the frequency range below the ion cyclotron frequency. In the dissipation range, the spectral index η is larger and varies from 3 to 5 (Denskat, Beinroth, and Neubauer, 1983; Leamon et al., 1998). Since the wave power at ion cyclotron frequency range is too low to heat or accelerate the solar wind (Marsch, Goertz, and Richter, 1982), it is often assumed that turbulence efficiently transfers wave energy from larger scales to smaller scales, or from the low frequency to the ion cyclotron frequency range (Li et al., 1999). In this study we adopt the same assumption and set $\eta = 2$.

Quasi-linear theory of ion cyclotron resonance is adopted to calculate how the ion cyclotron wave energy is apportioned to protons and alpha particles in the solar wind (Isenberg, 1984a):

$$Q_{i\perp} = \rho_i (q_i/m_i)^2 (m_i/T_{i\|})^{1/2} \int_0^{k_{max}} dk_\| \, \frac{P(k_\|)}{k_\|} (\Omega_i/k_\|) H_i \qquad (3)$$

$$Q_{i\|} = \rho_i (q_i/m_i)^2 (m_i/T_{i\|})^{1/2} \int_0^{k_{max}} dk_\| \frac{P(k_\|)}{k_\|} [(\omega - \Omega_i)/k_\| - u_i] H_i \qquad (4)$$

where

$$H_i = \{\Omega_i/k_\| + [(\omega - \Omega_i)/k_\| - u_i]\Gamma_i\} \cdot$$
$$\exp\{-m_i (2k_B T_{i\|})^{-1} [(\omega - \Omega_i)/k_\| - u_i]^2\}, \qquad (5)$$

and ρ_i is the mass density of ion species i, k_{max} is the maximum wave number of ion cyclotron waves. When the dispersion relation is similar to the one in Figure 3a (lower branch), in which there is a maximum frequency, k_{max} is assumed to be the wave number at the maximum frequency. Beyond this wave number, the group velocity of the ion cyclotron waves is negative (toward the Sun). When the dispersion relation is like the one in Figure 3c (thin solid line), in which both frequency and wave number change monotonically, k_{max} is simply defined as infinite.

When using Equations (3)–(5) to calculate the heating rate of a species, the phase speed $\omega/k_{\|}$ has to be calculated by solving the dispersion relation Equation (1). According to the quasi-linear theory, only the real part of ω is utilized in Equations (3)–(5). Hence, the quasi-linear theory is only valid when $|\gamma|/\omega \ll 1$.

3. Results

3.1. Ion cyclotron resonance in a warm electron-proton-α plasma typical of the inner corona

In this section we present examples of ion cyclotron resonance in a solar wind plasma including protons, alpha particles and electrons. The abundance of alpha particles is taken to be $n_\alpha/n_p = 0.05$, which is the typical value observed in the fast solar wind. The first example shown in Figure 1 is for a low plasma beta value $\beta_{p\|} = w_{p\|}^2/v_A^2 = 0.026$, typical of the solar wind acceleration region, i.e., in the first few solar radii. Total and individual heating rates (normalized to the total heating rate $Q = Q_p + Q_\alpha$, where $Q_p = Q_{p\perp} + Q_{p\|}$ and $Q_\alpha = Q_{\alpha\perp} + Q_{\alpha\|}$) are plotted as a function of $(u_\alpha - u_p)/v_A$, the velocity difference between alpha particles and protons normalized to the Alfvén speed.

UVCS observations indicate that an anisotropy of $\Gamma = T_\perp/T_\| > 1$ is found in the inner corona for both protons and oxygen ions O^{+5}, and that oxygen ions are flowing much faster than protons (Kohl et al., 1998; Li et al., 1998). At present, there are no observations regarding the temperature anisotropy of alpha particles in the inner corona. Since we assume ion cyclotron waves are responsible for the solar wind heating and acceleration, we take $\Gamma_p = 2$ and $\Gamma_\alpha = 2$ as an example. When $(u_\alpha - u_p)/v_A$ is small (< 0.05), ion cyclotron waves primarily heat alpha particles. At values of $u_\alpha - u_p \geq 0.1 v_A$, protons suddenly pick up the energy. Alpha particles lose their resonance with ion cyclotron waves beyond $0.4 v_A$ (Figure 1a). It is seen in Figure 1b and 1c that ion cyclotron waves preferentially heat protons and alpha particles in the direction perpendicular to the magnetic field and cool them in the direction parallel to the magnetic field (Li et al., 1999). Numerical simulations have also demonstrated that ion cyclotron waves generated by ion cyclotron instability due to the temperature anisotropy of the protons produce perpendicular heating to alpha particles (Cuperman, Ofman and Dryer, 1986, 1988). Our result of small relative velocity $(u_\alpha - u_p)/v_A$ supports those studies. Figure 1 also implies that the heating and acceleration of alpha particles must be fast. Otherwise protons will not get sufficient heating, which is in contrast with UVCS observations. Hence, we predict that, in the inner corona where the ion cyclotron frequency is as high as 100 – 10000 Hz, alpha particles will be already flowing faster than protons (Li et al., 1997; Hu and Habbal, 1998).

The parallel heating is sensitive to the anisotropy Γ_i (see Equation (5)). When Γ_α is large, $Q_{\alpha\|}$ could be positive. Shown in Figure 2 is an example where Γ_α is 4.5 while the other parameters are the same as in Figure 1. It is seen from Figure 2b that $Q_{\alpha\|}$ is positive when $(u_\alpha - u_p)/v_A$ is < 0.15, and alpha particles acquire parallel heating from ion cyclotron resonance. However, a large anisotropy of Γ_α tends to excite an ion cyclotron instability. When $0.15 < (u_\alpha - u_p)/v_A < 0.5$, $Q_\alpha < 0$, ion cyclotron instability tends to limit the growth of the temperature anisotropy Γ_α, or it is likely that Γ_α cannot reach 4.5 in this case.

To illustrate the dramatic energy distribution change between protons and alpha particles in Figures 1 and 2, we plot the dispersion relation (left panel) and growth rate (right panel) of ion cyclotron waves in Figure 3 using the parameters of Figure 2. Since there are two ion species in the plasma, the ion cyclotron wave dispersion relation has two branches (see lines with different thickness). When $u_\alpha - u_p$ is zero, there is a gap between the two branches. Since we assume the spectra of ion cyclotron waves are Alfvén waves at low frequencies, the ion cyclotron waves responsible for the solar wind heating must adopt the dispersion branch through zero frequency (thin solid line in Figure 3a), which corresponds to the alpha branch in a cold plasma dispersion relation. In this case, the ion cyclotron waves primarily heat the alpha particles, and the protons are not in resonance with the waves. However, the existence of a differential speed $(u_\alpha - u_p)/v_A = 0.2$ can make the two branches touch. A mode conversion happens in this case, and the ion cyclotron waves change from the alpha to the proton branch as the wave number increases. In the right panel of Figure 3, the solid and dashed lines represent wave growth (positive values of γ) and damping (negative values of γ), respectively (in the left and right panels, lines with the same thickness represent the same mode). It is seen that ion cyclotron instabilities can develop quite strongly. However, the ion cyclotron instabilities in Figures 3b and 3d are excited only by the anisotropy of alpha particles. When the abundance of alpha particles is 0, and protons have the same parameters of Figures 3c and 3d, no ion cyclotron instability is excited (see dispersion and growth rate in

Figures 3e and 3f). In the case of $u_\alpha - u_p = 0$ (Figures 3a and 3b), the range of wave numbers in the ion cyclotron instability is smaller than that in the case of $u_\alpha - u_p = 0.2 v_A$ (Figures 3c and 3d). This is because alpha particles are strongly in resonance with ion cyclotron waves when $u_\alpha - u_p = 0$ and the damping restrains the growth of ion cyclotron instabilities. As alpha particles flow faster, most alpha particles will lose resonance with ion cyclotron waves, and the ion cyclotron instabilities caused by the anisotropy of alpha particles show up. Of course, these instabilities will limit the further development of the anisotropy Γ_α.

3.2. Ion cyclotron resonance in a warm electron-proton-α plasma typical of interplanetary space

Next we explore the ion cyclotron resonance in a warmer plasma which is typical of the solar wind in interplanetary space. It has been commonly found that the core distribution of protons has a temperature anisotropy of $T_\perp / T_\parallel > 1$ in fast solar wind streams (Feldman et al., 1973, 1974; Marsch et al., 1982a). However, $T_{\alpha\perp}/T_{\alpha\parallel} < 1$ (in the core of the alpha particle distribution) is commonly found, in contrast to the proton distributions with $T_{p\perp}/T_{p\parallel} > 1$ (Marsch et al., 1982b). In interplanetary space (i.e., 0.3 – 1 AU), $u_\alpha - u_p \approx v_A$. Hence Marsch et al. (1982b) suggested that "the two ion species are affected differently by the processes that heat the solar wind streams". Here we demonstrate that ion cyclotron waves indeed affect protons and alpha particles differently.

In Figure 4, parameters are chosen such that: $\beta_{p\|} = w_{p\|}^2/v_A^2 = 0.2$, $\Gamma_p = 2$, $\Gamma_\alpha = 1.5$, $T_{\alpha\|}/T_{p\|} = 4$ and $n_\alpha/n_p = 0.05$. When $u_\alpha - u_p$ is small (i.e., $< 0.2v_A$), both protons and alpha particles receive perpendicular heating and parallel cooling, and protons get more heating than in a less warm plasma, such as in Figures 1 and 2. This is because in a warm plasma, the two branches of the dispersion relation of ion cyclotron waves have already touched like in Figure 3c (not shown here). Hence, both protons and alpha particles are in resonance with waves (Isenberg, 1984b). However, when $u_\alpha - u_p > 0.45v_A$ the alpha particles acquire a parallel heating and perpendicular cooling while protons still get parallel cooling and perpendicular heating. In this velocity range, ion cyclotron waves affect protons and alpha particles very differently: while ion cyclotron waves still tend to increase the anisotropy of protons they tend to decrease the anisotropy of alpha particles. Dusenbery and Hollweg (1981) conducted a similar study on the ion cyclotron resonance. However, since the effect of alpha particles on the ion cyclotron wave dispersion relation was ignored in their study, and they adopted a cold plasma dispersion relation, they failed to notice this phenomenon.

To further illustrate the difference of the influence of ion cyclotron waves on the protons and alpha particles, we calculate the heating rates by setting $(u_\alpha - u_p) = v_A$ and keeping other parameters in Figure 4 unchanged while changing Γ_α. The result is shown in Figure 5. The same influence of ion cyclotron waves on alpha particles as in Figure 4 is found to exist as long as $\Gamma_\alpha > 0.65$.

3.3. Ion cyclotron resonance: velocity space diffusion

Until now, an explanation has not been provided for why the ion cyclotron waves can affect protons and alpha particles differently in different parts of the parameter space. It is well known that the quasi-linear theory of ion cyclotron resonance can be qualitatively explained by particle diffusion in velocity space, whereby resonant particles are constrained to diffuse along specific surfaces (Kennel and Englemann, 1966; Dusenbery and Hollweg, 1981)

$$(v_\parallel - \omega/k_\parallel)^2 + v_\perp^2 = \text{const.} \tag{6}$$

These surfaces are called single-wave characteristics, and are curves of constant particle energy measured in the coordinate system moving with the wave phase velocity. These interpretations are only valid for nondispersive waves. However, they can be used to explain our results in a qualitative and physical sense.

Consider protons and alpha particles with temperature anisotropy of $\Gamma > 1$ as shown in Figure 6. Let the dotted (dashed) lines represent the contours of proton (alpha particle) velocity distribution. The big solid circle whose center is the phase speed of a wave, which is smaller than v_A, is a single-wave characteristic. Since diffusion proceeds from higher to lower density regions, the arrows on the big solid circle represent the direction of resonant particle diffusion (note, only protons with $v_\parallel < 0$ can be in resonance with waves; if $u_\alpha - u_p \approx 0$, all alpha particles can be in resonance with waves). In this case, the parallel velocity will be compressed and the perpendicular velocity spreads out. The result is parallel cooling and perpendicular heating. It is easy to understand that if $u_\alpha - u_p << v_A$, parallel cooling and perpendicular heating will occur for alpha particles as well.

Next let us assume that alpha particles are flowing much faster ($u_\alpha - u_p$ is around v_A). The dashed lines represent the contours of velocity distribution of alpha particles. The phase speed of waves resonant with alpha particles is generally larger than that of waves resonant with protons. Now the small solid line is one of the single-wave characteristics, and the arrows on it represent the direction of particle diffusion. Apparently, the parallel speed is spread out leading to parallel heating, and a perpendicular heating is expected. The difference in the influence of ion cyclotron waves on protons and alpha particles is due to the differential flow between alpha particles and protons. In a less warm plasma (Figures 1 and 2), this effect is negligible because when $u_\alpha - u_p \approx v_A$, the resonance between ion cyclotron waves and alpha particles is too small.

4. Discussion and Conclusions

In this study, we investigated the effect of the warm plasma dispersion relation on the heating of the solar wind protons and alpha particles. The existence of alpha particles is found to dramatically change the dispersion relation in a warm plasma typical of the solar wind plasma, and significantly affects the ion cyclotron resonance between ion cyclotron waves and solar wind ions. Alpha particles get most of the energy available from ion cyclotron waves when the relative speed between alpha particles and protons is small. Hence, if we assume that ion cyclotron waves are responsible for the solar wind heating and acceleration, we predict that alpha particles must be much faster than protons in most of the solar wind acceleration region, otherwise protons cannot get enough heating from ion cyclotron waves.

On the other hand, ion cyclotron waves affect the temperature anisotropy of protons and alpha particles differently in a warm plasma such as the solar wind 0.3 and 1 AU. When the relative speed between alpha particles and protons is about $0.5 - 1v_A$: ion cyclotron waves tend to increase the proton temperature anisotropy $\Gamma_p > 1$, and to yield alpha particles with a temperature anisotropy $\Gamma_\alpha < 1$.

We have assumed that the solar wind protons and alpha particles have bi-Maxwellian velocity distributions. Since ion cyclotron resonance affects only a portion of the particles in the velocity distribution, ion cyclotron resonance cannot maintain a bi-Maxwellian velocity distribution. A complete treatment will require a kinetic model (Isenberg, Lee, and Hollweg, 1999). It is well known that in situ measured velocity distributions cannot be described by bi-Maxwellians (Marsch et al., 1982a, 1982b). It is also known that thermal conduction may significantly change the solar wind proton velocity distribution away from bi-Maxwellian (Li, 1999; Olsen and Leer, 1999). On the other hand, in situ measured velocity distributions often exhibit a core, which may be approximately described by a bi-Maxwellian (Marsch et al., 1982a, 1982b). In the inner corona, ultraviolet spectral line measurements imply Gaussian line profiles (Kohl et al., 1997). Hence, we believe that this study is useful in our understanding of ion cyclotron resonance in the solar wind. The influence of non-Maxwellian distributions on the ion cyclotron resonance is beyond the scope of our study.

We also note that at larger wave numbers the damping rate of ion cyclotron waves is quite large, thus limiting the validity of quasi-linear theory. However, we have to keep in mind that we use a power law spectrum for ion cyclotron waves. At large wave numbers, the energy of the waves is very small and their contribution to ion cyclotron heating of the solar wind plasma is expected to be negligible. Hence the violation of quasi-linear theory at larger wave numbers is not expected to change our results significantly.

Our study based on the quasi-linear theory demonstrates the role of ion cyclotron waves in heating the solar wind ions and shaping their temperature anisotropy. However, to understand the ultimate consequences of ion cyclotron wave heating, a solar wind model is needed. Solar wind modeling is expected to yield the upper limits on the species temperature anisotropy since a large anisotropy leads to ion cyclotron instability.

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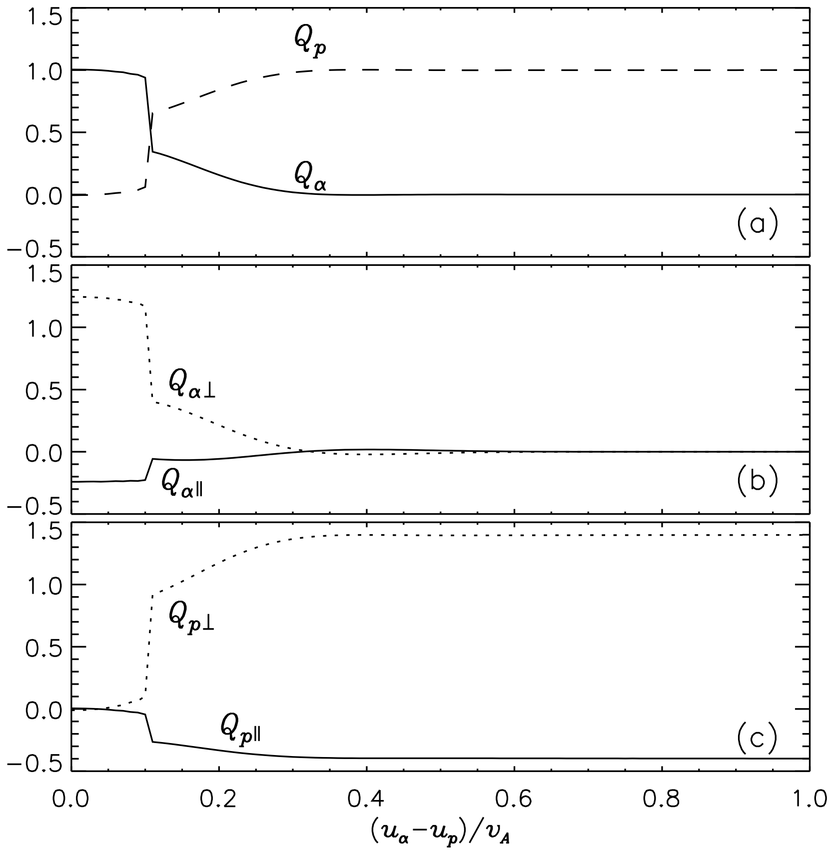

Figure 1. Heating rates normalized to total heating rate $Q_p + Q_\alpha$ as a function of $(u_\alpha - u_p)/v_A$ for $n_\alpha/n_p = 0.05$, $\Gamma_p = 2$, $\Gamma_\alpha = 2$, $\beta_{p\parallel} = 0.026$, $T_{\alpha\parallel}/T_{p\parallel} = 4$. (a) Total proton (alpha particle) heating rate Q_p (Q_α); (b) parallel and perpendicular heating rates of alpha particles $Q_{\alpha\parallel}$ and $Q_{\alpha\perp}$; (c) parallel and perpendicular heating rates of protons $Q_{p\parallel}$ and $Q_{p\perp}$.

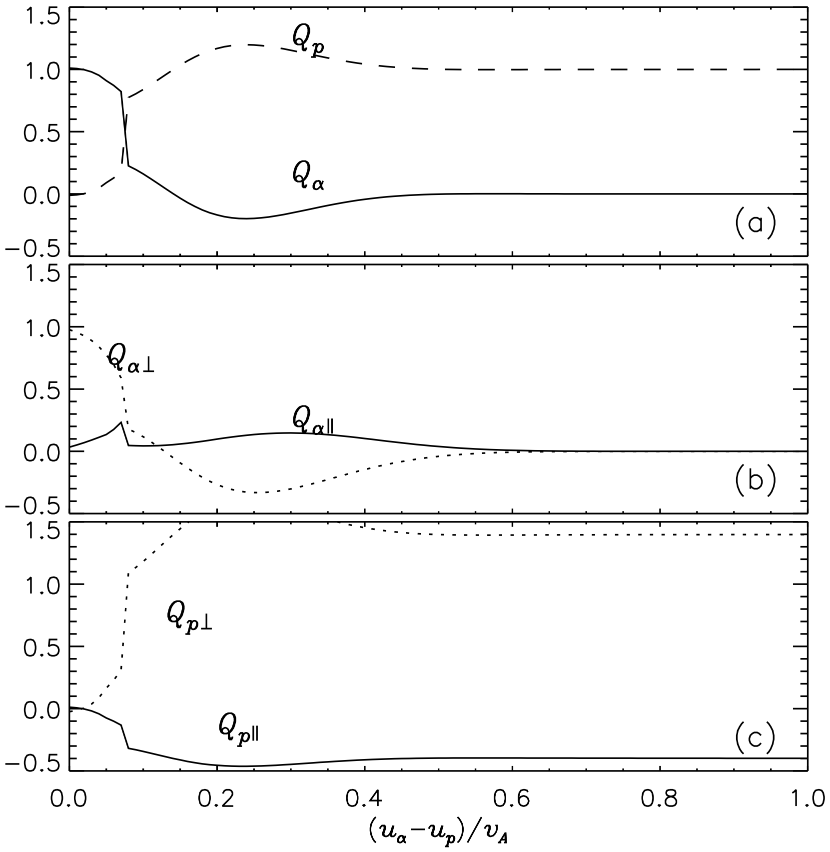

Figure 2. Similar to Figure 1 except $\Gamma_\alpha = 4.5$.

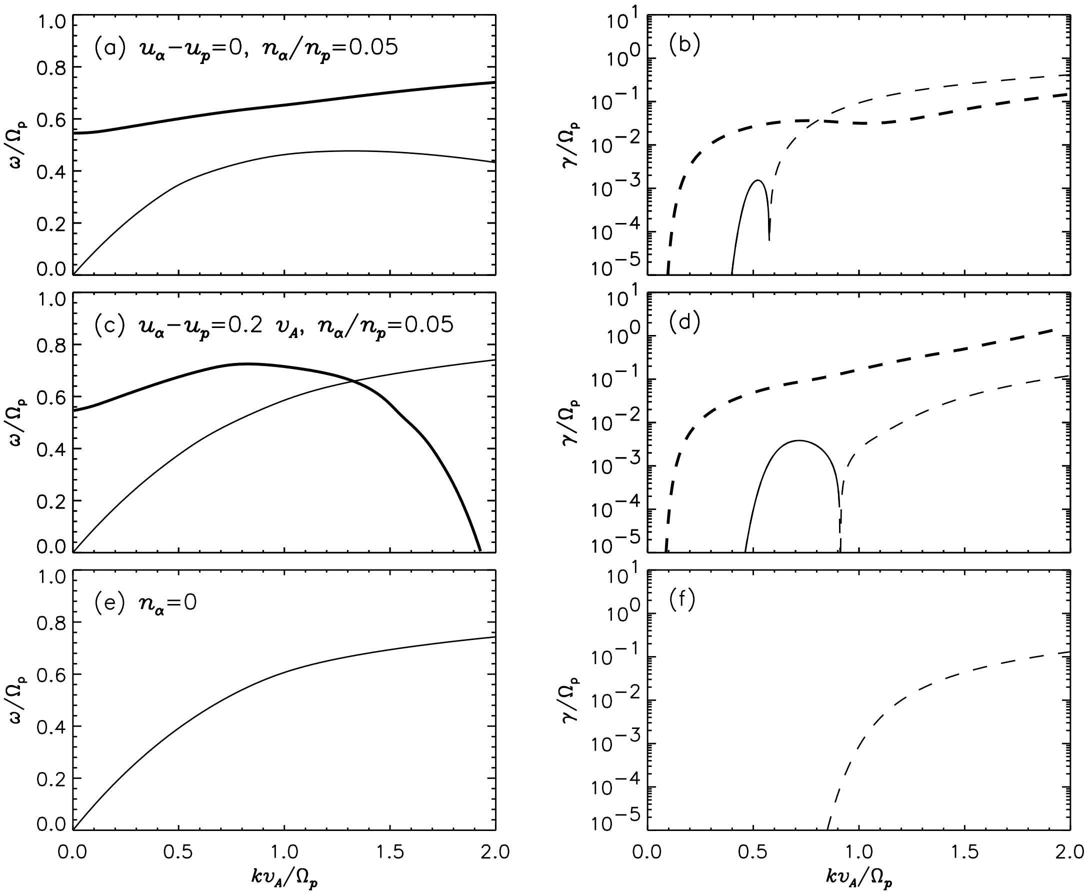

Figure 3. Dispersion relation (left panel) and growth rate (right panel) of ion cyclotron waves for cases from Figure 2. (a)-(b) case 1: $u_\alpha - u_p = 0$, $n_\alpha/n_p = 0.05$; (c)-(d) case 2: $u_\alpha - u_p = 0.2v_A$, $n_\alpha/n_p = 0.05$; (e)-(f) case 3: $n_\alpha/n_p = 0$. In the right panels, solid (dotted) lines represent growing (damping) modes.

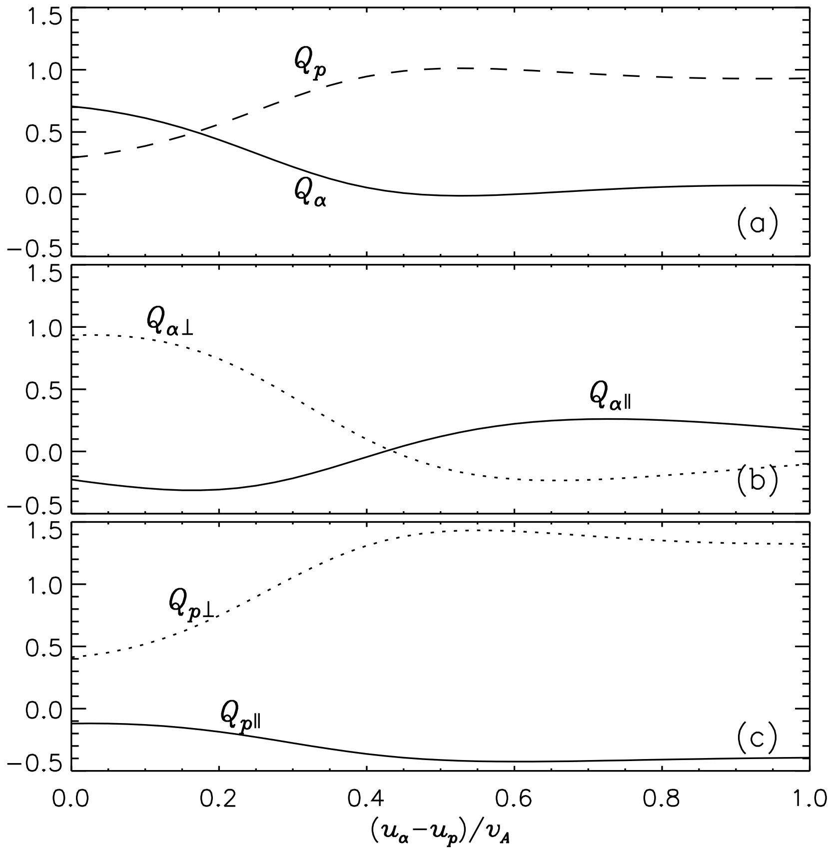

Figure 4. Similar to Figure 1 except $\beta_{p\parallel} = 0.2$ and $\Gamma_\alpha = 1.5$.

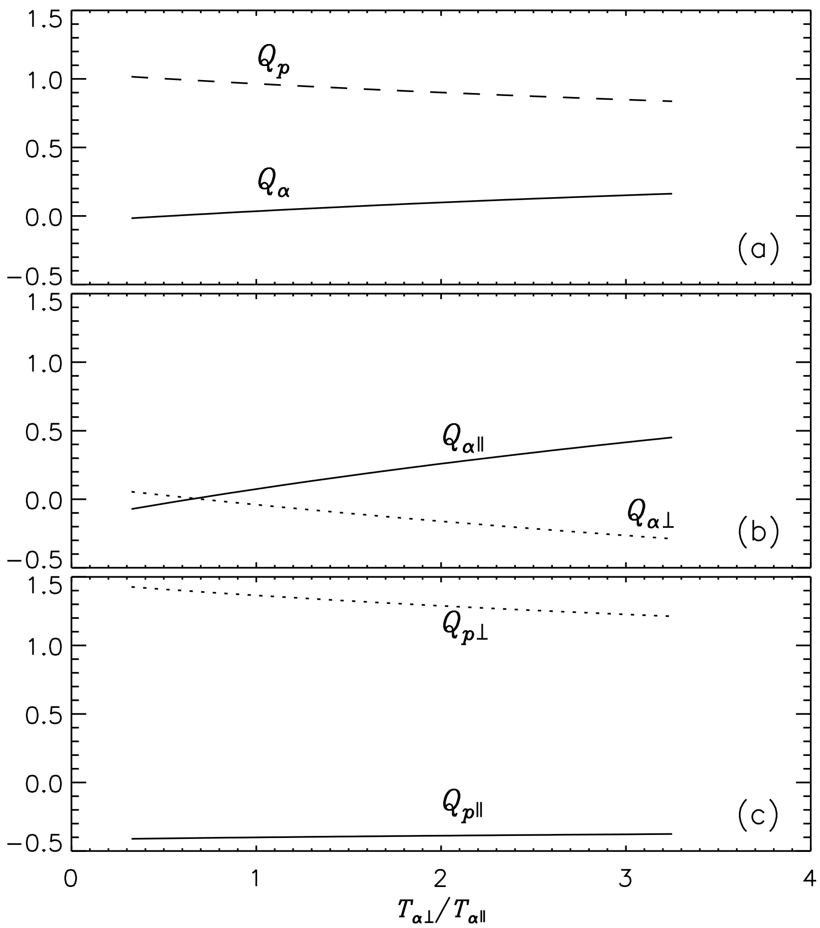

Figure 5. Heating rates normalized to total heating rate $Q_p + Q_\alpha$ as a function of $T_{\alpha\perp}/T_{\alpha\parallel}$. The following parameters are used: $n_\alpha/n_p = 0.05$, $\Gamma_p = 2$, $\beta_{p\parallel} = 0.2$, $T_{\alpha\parallel}/T_{p\parallel} = 4$, $u_\alpha - u_p = v_A$.

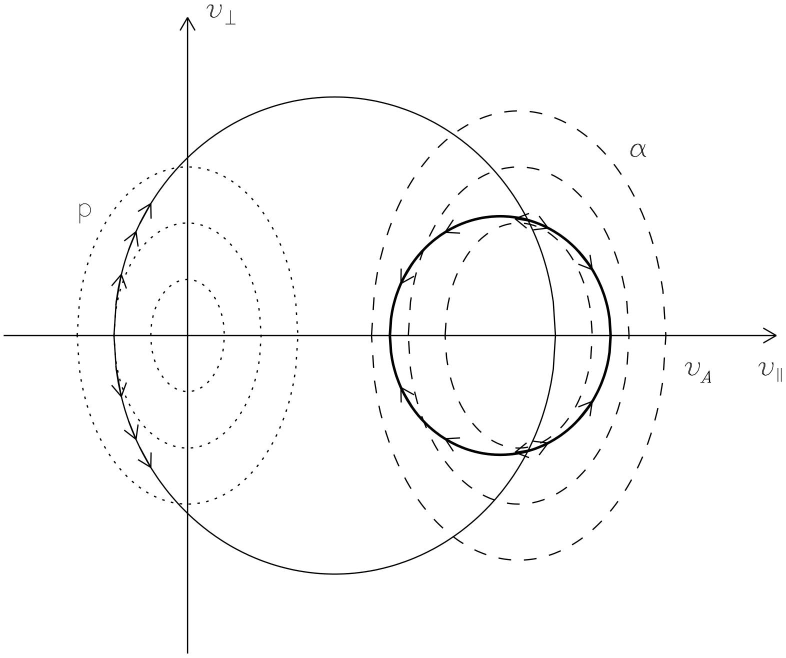

Figure 6. Velocity space diffusion via a spectrum of nondispersive waves. The solid circles represent single-wave characteristics which interact with the proton (dotted lines) and alpha particle (dashed lines) distribution. The arrows represent the direction of particle diffusion. Note, if the relative velocity between alpha particles and protons is zero, a parallel cooling and perpendicular heating will occur to both alpha particles and protons.