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Resonant wave-particle interactions modified by intrinsic Alfvénic turbulence

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The concept of wave-particle interactions via resonance is well discussed in plasma physics. This paper shows that intrinsic Alfvén waves can qualitatively modify the physics discussed in conventional linear plasma kinetic theories. It turns out that preexisting Alfvén waves can affect particle motion along the ambient magnetic field and, moreover, the ensuing force field is periodic in time. As a result, the meaning of the usual Landau and cyclotron resonance conditions becomes questionable. It turns out that this effect leads us to find a new electromagnetic instability. In such a process intrinsic Alfvén waves not only modify the unperturbed distribution function but also result in a different type of cyclotron resonance which is affected by the level of turbulence. This instability might enable us to better our understanding of the observed radio emission processes in the solar atmosphere. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4742989]

I. INTRODUCTION

Alfvén wave[1,2] is perhaps the most fascinating and intriguing wave mode that has attracted a great deal of interest in solar physics and astrophysics. Observations of Alfvén waves in the solar atmosphere and interplanetary space are well discussed in the literature.[3–6] It has been many years since the discovery of these waves, but their origin and generation mechanisms in the solar environments are still not clear. Issues and research efforts in this subject area are reported and discussed in a number of recent reviews.[7–9]

The purpose of the present discussion is not concerned with the explanation of specific observational issue in solar-terrestrial physics. We are interested in a fundamental question: can intrinsic turbulent Alfvén waves (ITAW hereafter) affect basic kinetic processes in solar plasmas? The topic is unstudied in the past and is challenging from theoretical viewpoint. The present study is motivated by three elementary considerations which are stated below.

First of all, in traditional linear kinetic theory it is generally assumed that the unperturbed plasma is quiescent. In other words the standard theory does not account for any preexisting waves. Second, the linear stability theories in plasma physics usually consider that the motion of each particle in unperturbed plasmas is basically determined by the ambient magnetic field and thereby the speed along a uniform ambient field, v_z, is a constant of motion. As we will show later, in the presence of ITAW v_z is no longer a constant of motion. Hence the unperturbed distribution function used in the usual theories of beam instability is not adequate. Third, when v_z is not a constant of motion, the derivations of the Landau resonance and cyclotron resonance are vitiated.

Motivated by these considerations we study a case in which a tenuous beam of energetic electrons emerges in addition to the thermal particles. It is well known in standard theory, which does not consider ITAW, that high-frequency electromagnetic waves cannot be excited by the beam electrons. Now we want to study what would happen if Alfvénic turbulence is present?

II. EFFECT OF ALFVÉNIC TURBULENCE ON ELECTRON MOTION

In the subsequent analysis we choose to work in the ITAW wave frame and moreover use the following assumptions: (a) the ITAW is considered as an ensemble of Alfvén waves with random phases; (b) the turbulence has homogeneous spectra energy; (c) nonlinear interactions among these Alfvén waves are not important in our theory; and (d) the energy density of ITAW is much lower than that of the ambient field (weak turbulence). No specific spectral model of the turbulence is needed in the discussion, as we will show later. To facilitate the analysis we consider that the ambient magnetic field $\mathbf{B}_0$ is along the z axis so that the wave magnetic fields are in the x-y plane. For simplicity we consider that the Alfvén waves are propagating along the ambient magnetic field and the waves are circularly polarized. Physically these intrinsic waves may be generated by tenuous energetic ions either via instabilities[10] or due to spontaneous process.[11] It can be seen later that the sense of polarization of the wave field does not change the essential physics. Hence without loss of generality we write the magnetic field of the Alfvén waves (in the wave frame) as[12]

$$\mathbf{B}_w = \sum_k B_k(\cos\phi_k \mathbf{i}_x + \sin\phi_k \mathbf{i}_y), \tag{1}$$

where $\phi_k = k_z z + \varphi_k$ is the wave phase, k_z is the wave number, and φ_k is the phase constant. The magnitude of $\mathbf{B}_w$ of the waves is spatially constant.

Our goal is to carry out a linearized theory in which ITAW is taken into account. We use an analytic approach so that the limit of weak turbulence, $B_w^2/B_0^2 \ll 1$, may be

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discussed and studied. First of all, we point out that under the influence of the wave magnetic field in Eq. (1) an approximate analytic solution is obtainable.[12] If $\bar{\mathbf{v}}(\tau)$ denotes the velocity of an electron at time τ and if we consider $B_w^2/B_0^2 \ll 1$, then we find

$$\bar{v}_z(\tau) = v_z - v_\perp \sum_k \frac{B_k}{B_0}\{\cos(\Phi_k - \Omega_e\tau) - \cos\Phi_k\} - v_z \sum_k \sum_{k'} \left\{\frac{B_{k'}B_k}{B_0^2}\cos(\phi_k - \phi_{k'})\right\}(1 - \cos\Omega_e\tau), \tag{2}$$

$$\bar{v}_\perp(\tau) \approx v_\perp \exp(i\alpha + i\Omega_e\tau) + v_z \sum_k \exp(i\alpha + i\phi_k)\frac{B_k}{B_0}(\exp i\Omega_e\tau - 1), \tag{3}$$

where $\Phi_k = \alpha + \phi_k$, α is a gyro phase angle, the phase ϕ_k is supposed to be random for turbulent waves and $\Omega_e = eB_0/m_ec$ is the electron gyro frequency, and m_e is electron mass. In obtaining Eqs. (2) and (3) we have used the initial condition $\bar{\mathbf{v}}(\tau = 0) = \mathbf{v}$. The last term of Eq. (2), which is due to second order perturbation, is easily understandable from the analysis presented in Ref. 12. The important point is that it gives rise to an oscillatory motion.

Most of the terms in Eqs. (2) and (3) are statistically unimportant due to the random wave phases. In fact all terms proportional to the wave field are small in comparison with speed of the energetic electrons. By definition we write $\bar{v}(\tau) = \langle\bar{\mathbf{v}}(\tau)\rangle + \delta\mathbf{v}$, where $\langle\rangle$ denotes an averaging operation over the wave phase and $\delta\mathbf{v}$ is the fluctuation velocity. Considering $|\langle\bar{\mathbf{v}}(\tau)\rangle| \gg |\delta\mathbf{v}|$ for energetic electrons and making use of the random phase approximation we find

$$\bar{v}_z(\tau) \approx \langle\bar{v}_z(\tau)\rangle = v_z - v_z\frac{B_w^2}{B_0^2}(1 - \cos\Omega_e\tau), \tag{4}$$

$$\bar{v}_\perp(\tau) \approx \langle\bar{v}_\perp(\tau)\rangle = v_\perp \exp(i\alpha + i\Omega_e\tau), \tag{5}$$

where the definition $B_w^2 \equiv \sum_k \langle B_k^2\rangle$ is used. Equation (4) manifests that the electron speed along the ambient magnetic field is no longer a constant of motion.

In principle, in the Alfvén wave frame the kinetic energy of a particle is conserved. But Eqs. (4) and (5) seem to give an impression that they are not in line with this expectation. A discussion is therefore called for. Let us go back to Eq. (3). If we define $\bar{v}_\perp^2(\tau) \approx \langle\bar{v}_\perp(\tau)\bar{v}_\perp^*(\tau)\rangle$, then it is found

$$\bar{v}_\perp^2(\tau) \approx v_\perp^2 + 2v_z^2\frac{B_w^2}{B_0^2}(1 - \cos\Omega_e\tau).$$

Hence if high order terms $O(B_w^4/B_0^4)$ are neglected, $\bar{v}_z^2 + \bar{v}_\perp^2$ is approximately constant. In short the analytic expression Eq. (5) is approximate. However, making use of such an approximate expression does not compromise the study of essential physical process, like wave-particle resonance.

To discuss the significance of Eq. (4) we pay attention to a special time integral that appears frequently in plasma kinetic theory.[13] It is defined as I

$$I \equiv \lim_{\Delta\to 0_+}\int_0^\infty d\tau \exp[ik_z(\bar{z}(\tau) - z) - i\omega\tau - \Delta\tau], \tag{6}$$

where ω and k_z denote frequency and wave number along z, respectively, and

$$\bar{z}(\tau) = \int_0^\tau d\tau'\bar{v}_z(\tau') = z + v_z\tau - \frac{B_w^2}{B_0^2}\frac{v_z}{\Omega_e}(\tau - \sin\Omega_e\tau) \approx z + v_z\tau + \frac{B_w^2}{B_0^2}\frac{v_z}{\Omega_e}\sin\Omega_e\tau. \tag{7}$$

Making use of Eqs. (6) and (7) one finds that the imaginary part of I or Im I is

$$\mathrm{Im}\, I \simeq \pi\sum_q \delta[(k_zv_z - \omega) + q\Omega_e]J_q(\rho),$$

where $\rho = (k_zv_z/\Omega_e)(B_w^2/B_0^2)$ and $J_q(\rho)$ is the Bessel function of order q. It represents a generalized resonance condition. If we set $\rho = 0$, it recovers the Landau resonance of waves propagating along the ambient magnetic field. This result implies that ITAW may result in significant modification of the usual resonance process.

III. A LINEARIZED KINETIC THEORY AND ESSENTIAL ASSUMPTIONS USED

In the following we describe the case to be studied. It is assumed that the kinetic energy density of a beam of energetic electrons is much lower than that of ITAW so that the self-consistently generated Alfvén waves are unimportant, and the ITAW is treated as preexisting. We will study the following linearized kinetic equation which includes ITAW

$$\frac{\partial f_s}{\partial t} + \mathbf{v}\cdot\frac{\partial f_s}{\partial \mathbf{r}} - \frac{e}{m_ec}\mathbf{v}\times(\mathbf{B}_0 + \mathbf{B}_w)\cdot\frac{\partial f_s}{\partial \mathbf{v}} = \frac{e}{m_e}\left(\delta\mathbf{E} + \frac{\mathbf{v}}{c}\times\delta\mathbf{B}\right)\cdot\frac{\partial F_s}{\partial \mathbf{v}}, \tag{8}$$

where f and F denote perturbation and unperturbed distribution functions, respectively, subscript s denotes electron species (s = 0 for ambient electrons and s = b for energetic beam electrons), m_e is electron mass, and $\delta\mathbf{E}$ and $\delta\mathbf{B}$ denote wave perturbation fields of interest. In such a system the beam density n_b is supposed to be much lower than the thermal electron density n_0. In the following we are concerned with high-frequency electromagnetic waves. Therefore, the ambient electrons are treated as if they are cold, and a delta function is used to represent their unperturbed distribution function. The unperturbed distribution function of the beam electrons is conventionally modeled by a bi-Maxwellian distribution,[1] e.g.,

$$F_b = A\exp\left[-\frac{(v_z - v_0)^2}{\alpha_z^2} - \frac{v_\perp^2}{\alpha_\perp^2}\right],$$

which is no longer appropriate if ITAW are present. To construct a proper unperturbed distribution functions one needs to consider some other constants of motion. For instance the particle energy and generalized momentum in the wave frame are two good candidates. The generalized momentum is of interest because it depicts implicitly the interaction between the wave field and particle motion. Sonnerup and Su,[14] Verscharen and Marsch,[15] and Nariyuki[16] have made use of these constants to discuss ion velocity distribution function under the influence of a large amplitude low frequency wave. On the basis of these constants Verscharen and Marsch[15] shows that observed apparent temperature anisotropy of ions in the solar wind may be explained in terms of wave effects. However, if the intrinsic turbulence consists of a spectrum of waves the generalized momentum is not a useful constant because it is associated with wave frequency and wave vector. For this reason we use magnetic moment and particle kinetic energy as the two constants of motion. The former is approximately justifiable if the wave energy density is low in comparison with that of the ambient magnetic field. We will discuss this point later.

Physically it is conceivable that in the Alfvén wave frame the velocity distribution function $F_b(\mathbf{v})$ of the energetic electrons can be conveniently described by a spherical coordinate system in which there are two variables: the speed v and $\mu = \cos\theta$ (where θ is the pitch angle). Both are defined in the Alfvén wave frame.

IV. DISPERSION EQUATIONS AND GROWTH RATES

Since the calculation of the perturbation distribution f as well as the derivation of desired dispersion equations with the field equations is standard[13] we shall only present the results and omit the detailed algebra of derivation. From past studies we have learned that electromagnetic waves with nearly perpendicular propagation usually yield high growth rates. In this case, the extraordinary (X) mode and ordinary (O) mode waves may be treated separately. Then the O-mode dispersion equation is found to be

$$1 - \frac{c^2k_\perp^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2} + \frac{n_b}{n_0}\frac{\omega_{pe}^2}{\omega} \times \sum_n\sum_q \int d\mathbf{v}\, \frac{\mu^2 v(1+\varepsilon q)J_n^2(p)J_q(\rho)}{[\omega - (n+q)\Omega_{e0}/\gamma - k_z v_z]} \times \left(\frac{\partial F_b(\mathbf{v})}{\partial v} - \frac{\mu}{v}\frac{\partial F_b(\mathbf{v})}{\partial \mu}\right) = 0. \tag{9}$$

The X-mode dispersion equation may be derived if we pay attention mainly to the electromagnetic component. Then the dispersion equation is

$$1 - \frac{c^2k^2}{\omega^2} - \frac{\omega_{pe}^2}{\omega^2 - \Omega_e^2} + \frac{n_b}{n_0}\frac{\omega_{pe}^2}{\omega} \times \sum_n\sum_q \int d\mathbf{v}\, \frac{v(1-\mu^2)\left(dJ_n(p)/dp\right)^2 J_q(\rho)}{[\omega - (n+q)\Omega_{e0}/\gamma - k_z\mu v]} \times \left(\frac{\partial F_b(\mathbf{v})}{\partial v} - \frac{\mu}{v}\frac{\partial F_b(\mathbf{v})}{\partial \mu}\right) = 0. \tag{10}$$

where $p = k_\perp v_\perp/\Omega_e$; $\rho = k_z v_z B_w^2/B_0^2\Omega_e$; $\varepsilon = \Omega_e/k_z v_z$; $J_n(\mathrm{p})$ and $J_q(\rho)$ are Bessel functions of order n and q, respectively, $dJ_n(p)/dp$ is the derivative; $\gamma = (1 - v^2/c^2)^{-1/2}$ is a relativistic factor; and Ω_{e0} is the rest mass electron gyro frequency. In Eqs. (9) and (10) the first three terms are due to the background electrons which are treated to be cold because the waves understudy have phase velocities higher than the speed of light (we use delta function to represent their distribution function). We keep the relativistic factor in the denominator of the terms due to the energetic electrons because for high frequency electromagnetic waves with refractive indices close to unity the relativistic effect can be crucial. It totally changes the resonance condition from a straight line, $v_z =$ resonance velocity, to an ellipse in velocity space. We shall return to this point latter. In obtaining the term due to energetic electrons in Eqs. (9) and (10) we have used the condition $\omega_k/k_z \geq c \gg v$, where c is the speed of light.

To study the above equations we write $\omega = \omega_k + i\gamma_k$ where ω_k denotes the wave frequency and γ_k the growth rate. The dispersion relation of the frequency ω_k is discussed by ignoring the energetic electrons and γ_k may be calculated by considering $|\gamma_k/\omega_k| \ll 1$. The results are presented below (here we note if $\gamma_k < 0$ it means damping or absorption and if $\gamma_k > 0$ means growth or negative absorption). For O-mode wave the wave frequency satisfies the dispersion relation $N^2 = 1 - \omega_{pe}^2/\omega_k^2$, where $N \equiv kc/\omega_k$ is the refractive index and ω_{pe} is the plasma frequency of the ambient electrons. The expression for growth rate is

$$\frac{\gamma_k}{\omega_k} = \frac{n_b}{n_0}\pi\frac{\omega_{pe}^2}{2\omega_k}\sum_n\sum_q\int d^3\mathbf{v}v\mu^2(1+\varepsilon q)J_n^2(p)J_q(\rho) \times \delta[\omega_k - (n+q)\Omega_{e0}/\gamma - k_z\mu v]\left(\frac{\partial F_b(\mathbf{v})}{\partial v} - \frac{\mu}{v}\frac{\partial F_b(\mathbf{v})}{\partial \mu}\right). \tag{11}$$

For X-mode, the expression for growth rate is

$$\frac{\gamma_k}{\omega_k} \approx \frac{n_b}{n_0}\pi\frac{(\omega_k^2 - \Omega_{e0}^2)^2}{2\omega_k^3}\sum_n\sum_q\int d^3\mathbf{v}v(1-\mu^2) \times \left(dJ_n(p)/dp\right)^2 J_q(\rho) \times \delta[\omega_k - (n+q)\Omega_{e0}/\gamma - k_z v\mu] \times \left(\frac{\partial F_b(\mathbf{v})}{\partial v} - \frac{\mu}{v}\frac{\partial F_b(\mathbf{v})}{\partial \mu}\right). \tag{12}$$

In Eqs. (11) and (12) the real frequency ω_k satisfies the cold electron dispersion relations. In performing numerical calculation of the X-mode growth rate we use a complete dispersion relation so that the cutoff frequency is accurately described.

V. MODEL OF THE UNPERTURBED DISTRIBUTION FUNCTION

To model the velocity distribution function of the beam electrons, we consider two points. (i) In the wave frame the speed v of each electron is a constant of motion because of conservation of energy. Moreover the magnetic moment (or $v_\perp^2 = (1-\mu^2)v^2$) is also approximately a constant of motion.

(ii) We expect that ITAW can affect the beam electrons via pitch-angle scattering. This expectation is shown by a test-particle simulation in which we consider $B_w^2/B_0^2 \ll 1$. In such a simulation the kinetic energy density of the electrons is supposed to be much lower than B_w^2, as we remarked earlier. The simulation results are depicted in Fig. 1(a). The conclusions are that, first, the time asymptotic beam distribution function deforms quickly into a crescent-shaped distribution and, second, the "pitch-angle width" of the distribution function, which depends upon the energy density of ITAW. Thus we model the beam electron distribution under the influence of ITAW as

$$F_b(v,\mu) = B\exp\left(-\frac{(v-v_0)^2}{\alpha^2} - \frac{(1-\mu^2)}{\beta^2}\right), \tag{13}$$

where B is a normalization constant, v_0 is the beam speed, α and β correspond to related dispersions, and $\mu = \cos\theta$ (where θ is the pitch-angle defined in the wave frame). The "width" β is determined by pitch-angle diffusion due to ITAW. On the basis of a preceding analytic study[17] we assume that $\beta^2 \approx 2B_w^2/B_0^2$. Hereafter we assume $\alpha^2 \ll v_0^2 B_w^2/B_0^2 \ll v_0^2$. Since in general an unperturbed distribution function is constructed on the basis of some "constants of motion" it only represents a mathematical solution. In obtaining such a solution some degree of arbitrariness is inevitable. Even if the chosen distribution function may be physically reasonable it does not mean that the distribution function is physically unique unless we can prove that. That is why we have conducted a numerical simulation.

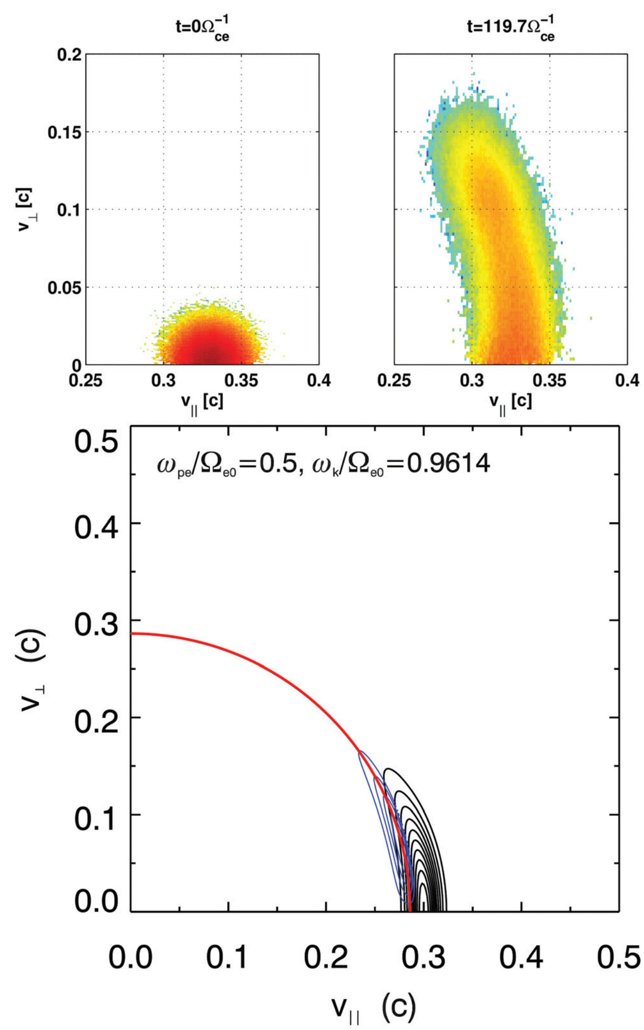

FIG. 1. (a) Test particle simulation shows that ITAW can affect the velocity distribution function of a simple energetic electron beam so that a crescent-shaped beam distribution is formed. (b) Contour plot of a crescent-shaped distribution function (black lines) described by Eq. (11). The blue lines represent the contours of the positive gradient of the beam distribution and the red circle depicts a resonance circle for a given frequency.

VI. A NEW ELECTROMAGNETIC INSTABILITY

Before going further we reiterate that in the stability theory of high-frequency electromagnetic waves it is important to include the relativistic effect on the cyclotron resonance condition. This effect qualitatively changes the resonance condition in velocity space as reviewed in the literature.[18,19] The best known case in space physics is the instability driven by a loss-cone type of velocity distribution of energetic electrons. In general the resonance condition is described by an ellipse in velocity space. We point out that for waves with nearly perpendicular propagation the resonance ellipse becomes a circle. In the present case we see from Eqs. (11) and (12) that instability occurs if

$$\left(\frac{\partial F_b(\mathbf{v})}{\partial v} - \frac{\mu}{v}\frac{\partial F_b(\mathbf{v})}{\partial \mu}\right)\Bigg|_{v=v_R} > 0,$$

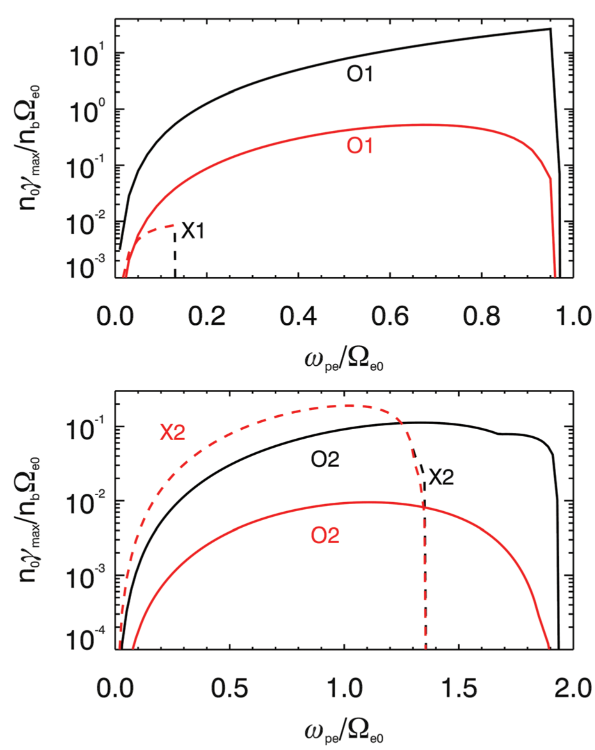

FIG. 2. Numerical results calculated from expressions (9), (10), and (11). Plots show variations of the maximum growth rates versus the frequency ratio ω_{pe}/Ω_{e0}. Panel (a) depicts the fundamental O-mode (solid lines) and X-mode (dash lines) waves whereas panel (b) shows the 2nd harmonic O-mode (solid lines) and 2nd harmonic X-mode (dash lines) waves. The black lines are for modes $(n+q) =$ (a) 1 and (b) 2; the red lines are just for the mode $(n, q) =$ (a) $(1, 0)$ and (b)$(2, 0)$.

where v_R denotes the resonant electron velocity and

$$v_R \approx c\sqrt{2\left(1 - \frac{\omega_k}{(n+q)\Omega_{e0}}\right)}.$$

Hence instability occurs if $v_0 - \alpha < v_R < v_0$, as illustrated graphically in Figure 1(b). To the best of our knowledge this type of beam instability has not been discussed before. Moreover, the usual cyclotron maser instability due to loss-cone type distributions mainly results in the emission of X-mode radiation, whereas the modified resonance condition shown in the growth rate Eq. (11) of the new instability indicates clearly that under certain condition O-mode radiation can prevail; for example, in the case $n = 0$ and $q = 1$). This point is verified with numerical results to be discussed later. Moreover, the nature of the new instability discussed in the present theory is very different from the well known ring-beam instability.[20]

VII. DISCUSSION AND CONCLUDING REMARKS

Numerical calculations based on Eqs. (11), (12), and (13) are carried out with the following parameters (i) $B_w^2/B_0^2 = 0.05$; (ii) $v_0 = 0.3c$; (iii) $\alpha = 0.05$; and (iv) $\beta = 0.32$ so that we plot the maximal growth rates (or negative absorption coefficient) of O-mode and X-mode waves versus the ratio ω_{pe}/Ω_e. The results are shown in Fig. 2. For abbreviation the fundamental and harmonic O-mode and X-mode waves are denoted by O1, X1, O2, and X2, respectively. Curves in red color represent the case without ITAW whereas curves in black color depict the case with Alfvén waves. Figs. 2(a) and 2(b) display the results accordingly. The essential conclusions are (i) ITAW have little effect on X1 wave while O1 wave is greatly affected. (ii) ITAW can affect both O2 and X2 waves. (iii) When $\omega_{pe}^2/\Omega_e^2 \ll 1$, the presence of ITAW both X1, X2, O1, and O2 waves can grow. (iv) When $\omega_{pe}^2/\Omega_e^2 \approx 1$, O1 waves prevail.

Finally we remark that although the present discussion is preliminary, it enables us to gain new insight. The instability discovered also implicates a new induced radiation process. The main conclusion acquired is that ITAW can play catalytic roles: the waves can qualitatively affect the velocity distribution of energetic electrons via pitch-angle scattering and at the same time they can also modify the usual cyclotron resonance processes. These findings may have interesting implications to the study of other kinetic processes in solar plasmas.

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