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The Propagation and Absorption of Oblique Alfvén Waves in a Dusty Plasma

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In situ observations performed by spacecraft in the interplanetary space have shown convincing evidence of the existence of dust particles in the solar system [1]. The charged dust particles can modify the dielectric properties of the plasma, both in the propagation and in the absorption of waves, and can also lead to the appearance of entirely new propagation modes.

On the other hand, Alfvén waves present in the solar wind environment have been proposed as a possible accelerating mechanism for the solar wind [2]. Since both the damping and propagation of Alfvén waves may be affected by the presence of dust, we have started studies on the behavior of these waves in a dusty plasma [3]. We have shown that in the presence of charged dust particles the characteristics of Alfvén waves are modified. In particular, the absorption rates are increased, and several couplings between distinct branches of the dispersion relation appear, both features related to the variation of the dust electric charge. The growth rate of instabilities appearing in anisotropic plasmas can also be affected by the presence of the dust [3].

Here we report a recent theoretical evidence [4] that the presence of dust in the solar wind can substantially alter the long wavelength dynamics of the kinetic Alfvén waves (KAW), as compared to the usual behavior in a conventional plasma. It will be seen that in the frequency range considered in this work, the dust particles modify the dispersion relation through modifications of the quasineutrality condition and through effects due to dust-charge variation.

In our kinetic formulation we consider a homogeneous magnetized electron-proton plasma tainted with spherical dust grains with constant radius a and variable charge q_d, which is always negative, due to the higher mobility of the electrons. The cross-section for the charging process of the dust particles is evaluated using the OML (orbital motion limited) theory [5]. Dust particles are assumed to be immobile, and consequently the validity of the proposed model will be restricted to waves with frequency much higher than the characteristic dust frequencies. In particular, we will consider the regime in which $|\Omega_d| \ll \omega \ll |\Omega_\beta|$, where Ω_d and Ω_β are the cyclotron frequencies of the dust particles and of electrons and ions, respectively. Assuming B_0 along the z direction, and the wave vector on the $x-z$ plane, the dispersion relation is [4]

$$\left[\left(\frac{z^2}{\eta_i^2}+\varepsilon_{yy}^1-q_z^2\right)\left(\frac{z^2}{\eta_i^2}+\varepsilon_{xx}^1-q_z^2\right)-\left(\varepsilon_{xy}^1\right)^2\right]\left(\frac{z^2}{\eta_i^2}+\varepsilon_{zz}^0\right)+\left\{\left(\frac{z^2}{\eta_i^2}+\varepsilon_{xx}^1-q_z^2\right)\left(\varepsilon_{yy}^0-1\right)\right.$$
$$\times\left(\frac{z^2}{\eta_i^2}+\varepsilon_{zz}^0\right)+\left(\frac{z^2}{\eta_i^2}+\varepsilon_{yy}^1-q_z^2\right)\left[\left(\frac{z^2}{\eta_i^2}+\varepsilon_{xx}^1-q_z^2\right)\left(\varepsilon_{zz}^1-1\right)-\left(\varepsilon_{xz}^1+q_z\right)^2\right]$$
$$\left.-\left[\left(\varepsilon_{xy}^1\right)^2\left(\varepsilon_{zz}^1-1\right)-2\varepsilon_{xy}^1\varepsilon_{yz}^1\left(\varepsilon_{xz}^1+q_z\right)+\left(\varepsilon_{yz}^1\right)^2\left(\frac{z^2}{\eta_i^2}+\varepsilon_{xx}^1-q_z^2\right)\right]\right\}q_\perp^2$$
$$+\left(\varepsilon_{yy}^0-1\right)\left[\left(\frac{z^2}{\eta_i^2}+\varepsilon_{xx}^1-q_z^2\right)\left(\varepsilon_{zz}^1-1\right)-\left(\varepsilon_{xz}^1+q_z\right)^2\right]q_\perp^4=0, \quad (1)$$

where $z=\omega/\Omega_i$, $\eta_i=\omega_{pi}/\Omega_i$, $q=kv_A/\Omega_i$, v_A is the Alfvén speed and $\varepsilon_{ij}^{0,1}$ are the components of the dielectric tensor. Details on the derivation of Eq. (1) are given in Ref. [4].

Equation (1) was solved for several different parameters, with the following kept constant: $T_i=10^4$ K, $n_{i0}=10^9\,\mathrm{cm}^{-3}$, $B_0=1$ G, $a=10^{-4}$ cm, and $\tau_e=T_e/T_i=1$. Figure 1 shows the dispersion of waves with $q_\perp=0.1$. The continuous curves are identified as the forward propagating ion cyclotron wave, whereas the dot-dashed curves are the backward-propagating ion cyclotron mode. The dashed lines depict the dispersion and absorption of the fast Alfvén/whistler mode. See Ref. [4] for a detailed description about the identification and evolution of the modes. For all values of $\varepsilon=n_d/n_{i0}$ (dust-ion density ratio), there is always a range of q_z in which these waves are nonpropagating. Within this range, the nonpropagating region has two different values of z_i, meaning that oscillations with very low frequency are globally absorbed in this q_z interval. Outside this range, the mode becomes dispersive again and the imaginary part for both directions of propagation is the same. Fig. 1 shows a strikingly different behavior from that observed in a dustless plasma and even from parallel propagation in a dusty plasma [3].

In Figure 2, one can observe that for the full interval where the forward/backward shear Alfvén waves are nonpropagating, z_i has again two distinct values which become the same when the modes start having a nonzero group velocity. As $q_\perp$ increases, the curves for the

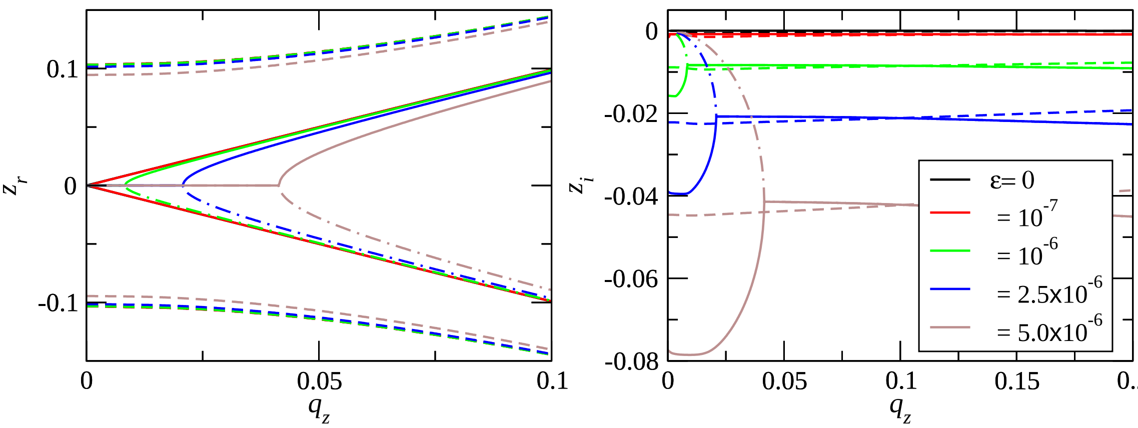

Figure 1: Real (z_r) and imaginary (z_i) parts of z as a function of q_z for $q_\perp=0.1$.

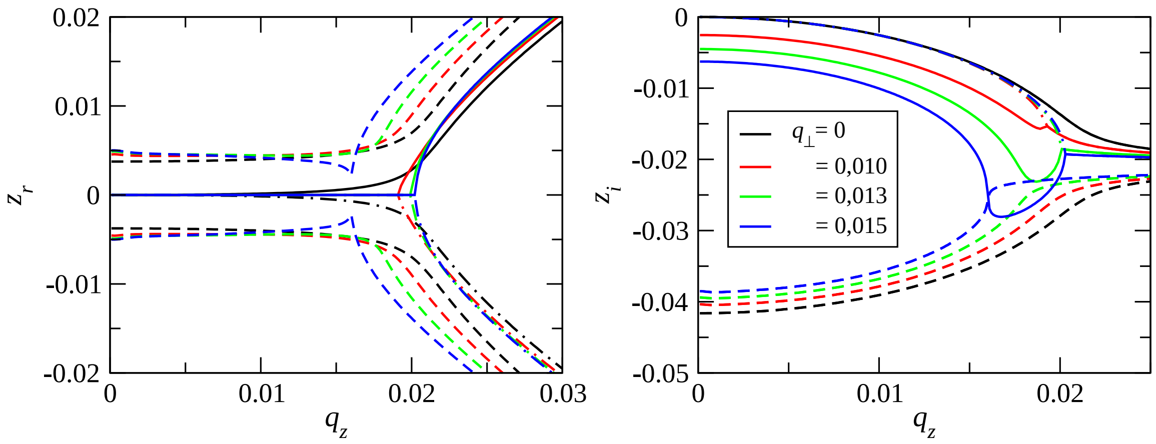

Figure 2: Plots of z *versus* q_z for $\varepsilon = 2.5 \times 10^{-6}$ and various values of $q_\perp$.

forward propagating shear Alfvén waves (continuous line) eventually overlap with the whistler waves (see right panel). On the same value of q_z where this overlap starts, the curves of z_r for the whistler modes pinch toward $z_r = 0$ and then increase again.

The pinching of z_r for the whistler waves becomes more pronounced for higher values of $q_\perp$, and a finite interval of q_z appears, wherein all the modes become nonpropagating. This situation is depicted in Figure 3, where three distinct dispersive regions can be distinguished. On the left panel these regions are distinguished by the number of propagating modes that exist (2, 0 or 4) and on the right panel the regions are delimited by the coupling points C_1, C_2 and C_3.

The evolution of the different dispersive regions is shown in Figure 4, for $q_\perp = 0.018 \to 0.024$. One notices that region ***1*** vanishes at $q_\perp \simeq 0.0215$, and that region ***2*** vanishes at $q_\perp \simeq 0.022$. The coupling point C_3 remains unaffected by the variance of $q_\perp$, since it depends essentially on the dust density parameter ε. For higher values of $q_\perp$, the results of Fig. 1 are restored.

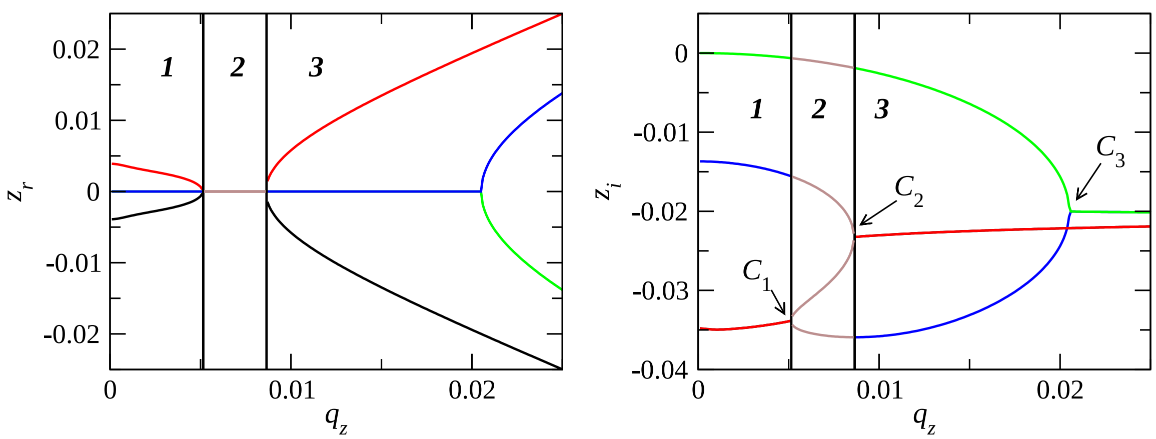

Figure 3: $z \times q_z$ for $\varepsilon = 2.5 \times 10^{-6}$ and $q_\perp = 0.02$. Red/black curves: forward/backward whistler modes, blue/green curves:forward/backward ion cyclotron modes. Brown curves: nonpropagating modes.

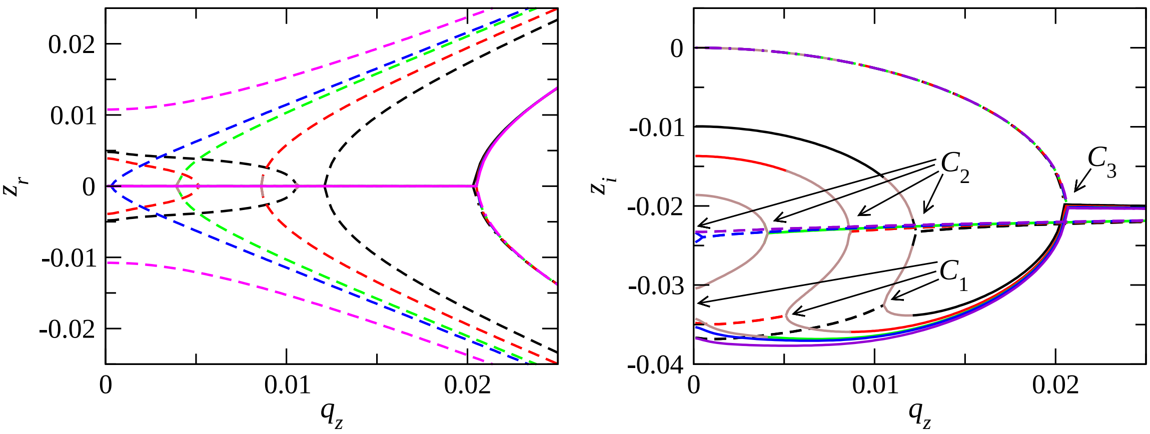

Figure 4: $z \times q_z$ for $\varepsilon = 2.5 \times 10^{-6}$ and several $q_\perp$. Curves follow convention of Fig. 1. Color codes are: — $q_\perp = 0.018$, — $q_\perp = 0.02$, — $q_\perp = 0.0215$, — $q_\perp = 0.022$, and — $q_\perp = 0.024$. Brown curves correspond to dispersive region ***2***.

The results presented in figures 1–4 show a substantial departure on the dispersion characteristics and the absorption coefficient of parallel and oblique-propagating Alfvén waves from the well-known behavior observed in dustless plasmas. The results strongly suggest that even a small amount of dust particles is sufficient to substantially modify the propagation and absorption of kinetic oblique Alfvén waves in the large wavelength limit. This assertion can have an important consequence on the research of space plasmas, since the Landau damping of kinetic Alfvén waves is supposed an important mechanism of dissipation for the Alfvénic turbulence in the solar wind or for particle acceleration in the magnetosphere [6].

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