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Ion-acoustic instability in a dusty negative ion plasma

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Abstract

The ion-acoustic instability in a dusty negative ion plasma is investigated, focusing on the parameter regime in which the negative ion density is much larger than the electron density. The dynamics of the massive dust grains are neglected, but collisions of electrons and ions with dust grains in addition to other collisional processes are taken into account. The presence of a population of charged dust can change the frequency of the fast wave, lead to additional damping due to ion–dust collisions, and change the conditions for wave growth. Applications to dusty negative ion plasmas in the laboratory and in space are discussed.

Keywords: Dusty plasma; Negative ion; Ion acoustic

1. Introduction

We consider a rather unusual dusty negative ion plasma in which the density of heavy negative ions is much larger than the electron density, by a factor of $\sim 10-1000$. There are several motivations for investigating this type of plasma, which have applications to both laboratory and space environments. Recently, Merlino et al. (2005) suggested that if a plasma has sufficient negative ion density, dust that is injected into the plasma could become positively charged because the dominant higher mobility species would be the positive ions. Very recently, Kim and Merlino (2006) have discussed the conditions under which dust injected into a laboratory negative ion plasma could become positively charged (for very large values of negative ion density on the order of >500 times the electron density). In regard to space dusty plasmas, recently Rapp et al. (2005) have discussed the possible role of negative ions in explaining their observations of positively charged nanoparticles in the mesosphere under nighttime conditions. Rapp et al. (2005) find that the dust could be positively charged if there is a sufficient number density of heavy negative ions (with mass greater than about 300 amu).

We consider the ion-acoustic instability in a plasma composed of almost equal number densities of heavy negative ions and light positive ions, relatively few electrons, charged dust, and background neutrals. It should be noted that D'Angelo (2004) has previously considered the excitation of ion-acoustic waves driven by streaming ions in a similar plasma, using a fluid analysis; the excitation of ion-acoustic waves by electron current was also mentioned in the latter paper. The present paper extends the study of D'Angelo (2004) to consider the kinetic regime of the electron current driven ion-acoustic instability, taking into account an external magnetic field and additional collisional effects such as electron and ion collisions with dust grains. Because the dust is too heavy to move on the time scale of the ion waves, we do not take the dynamics of the dust into account. However, dust carries some of the charge in the plasma and can also affect the ion and electron collision rates, which affects the wave dispersion and the conditions for wave growth.

The analysis is given in Section 2, which contains analytical results and numerical results with application to possible laboratory and space dusty negative ion plasmas. Section 3 gives a short summary.

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2. Analysis

We consider a plasma composed in general of singly charged positive ions, singly charged negative ions, electrons, charged dust, and neutral gas molecules. We assume that the negative ions are more massive than the positive ions, referring to the negative ions as 'heavy' and the positive ions as 'light.' The ratio of the heavy to light ion masses is denoted by M_r. Further, we consider the dust to be too massive to respond to perturbations on the time scale of the ion-acoustic waves; however, dust carries some of the charge so that the condition of overall charge neutrality is

$$n_{\mathrm{l}} \pm Z_{\mathrm{d}} n_{\mathrm{d}} = n_{\mathrm{h}} + n_{\mathrm{e}}, \tag{1}$$

where n_α is the density of charged species α (the subscript $\alpha = \mathrm{e, l, h, d}$ denotes electrons, light positive ions, heavy negative ions, and charged dust, respectively) Z_{d} is the dust charge state, and the upper, lower sign corresponds to positively, negatively charged dust, respectively. This condition can be written as

$$\delta = \frac{n_{\mathrm{l}}}{n_{\mathrm{e}}} = 1 + \varepsilon_{\mathrm{h}} \mp \varepsilon_{\mathrm{d}}, \tag{2}$$

where $\varepsilon_{\mathrm{h}} = n_{\mathrm{h}}/n_{\mathrm{e}}$ and $\varepsilon_{\mathrm{d}} = Z_{\mathrm{d}} n_{\mathrm{d}}/n_{\mathrm{e}}$, and again the upper, lower sign corresponds to positively, negatively charged dust, respectively.

We assume the plasma is homogeneous with a magnetic field $\mathbf{B}$ in the positive z-direction. The electrons and heavy ions drift in the z-direction, while the light ions drift in the $-z$ direction, due for example, to an external electric field $-E_0\mathbf{z}$. The magnitude of these drifts are

$$u_{0j} = \frac{eE_0}{m_j \nu_j}, \tag{3}$$

where m_j and ν_j, are the mass and collision frequency, respectively, of species $j = \mathrm{e, l, h}$. For the rates of electron and ion collision rates with neutrals or dust grains, we have respectively,

$$\nu_{j\mathrm{n}} \sim \sigma_{j\mathrm{n}} n_{\mathrm{d}} v_j, \tag{4a}$$

$$\nu_{j\mathrm{d}} \sim \sigma_{j\mathrm{d}} n_{\mathrm{d}} v_j. \tag{4b}$$

Here $\sigma_{j\mathrm{n}}$, $\sigma_{j\mathrm{d}}$ are the collision cross sections with neutrals and dust, respectively, n_{n} and n_{d} are the neutral density and dust density, respectively, and $v_j = (T_j/m_j)^{1/2}$ is the thermal speed of species j, with T_j and m_j being the temperature and mass, respectively. For the Coulomb collisions which we denote by $\nu_{\mathrm{C}j}$, we use expressions from Huba (2000).

Using drifting Maxwellian distributions for the electrons and ions, the dispersion relation for electrostatic waves with perturbed electric field $E_1 \sim \exp(\mathrm{i}\mathbf{k}\cdot\mathbf{r} - \omega t)$, frequency $\omega \ll$ the electron gyrofrequency Ω_{e} and $\gg$ the light ion gyrofrequency Ω_{l}, having wavevector components $k_\perp$ and k_z perpendicular and parallel to B, respectively, is given by (see e.g., Miyamoto, 1989; Kindel and Kennel, 1971)

$$D(\omega, k) = 1 + \sum_\alpha \chi_\alpha = 0, \tag{5}$$

where

$$\chi_{\mathrm{e}} = \frac{1}{k^2 \lambda_{\mathrm{De}}^2}[1 + \zeta_{\mathrm{e}} \Gamma_0(b_{\mathrm{e}}) Z(\zeta_{\mathrm{e}})] \left[1 + \frac{\mathrm{i}\nu_{\mathrm{e}}}{\sqrt{2} k_z v_{\mathrm{e}}} \Gamma_0(b_{\mathrm{e}}) Z(\zeta_{\mathrm{e}})\right]^{-1}, \tag{6}$$

$$\chi_{\mathrm{l,h}} = \frac{1}{k^2 \lambda_{\mathrm{Dl,h}}^2}[1 + \zeta_{\mathrm{l,h}} Z(\zeta_{\mathrm{l,h}})] \left[1 + \frac{\mathrm{i}\nu_{\mathrm{l,h}}}{\sqrt{2} k v_{\mathrm{l,h}}} Z(\zeta_{\mathrm{l,h}})\right]^{-1}. \tag{7}$$

Here

$$\zeta_{\mathrm{e}} = \frac{\omega - k_z u_{0\mathrm{e}} + \mathrm{i}\nu_{\mathrm{e}}}{\sqrt{2} k_z v_{\mathrm{e}}}, \tag{8}$$

$$\zeta_{\mathrm{l,h}} = \frac{\omega - \mathbf{k}\cdot\mathbf{u}_{0\mathrm{l,h}} + \mathrm{i}\nu_{\mathrm{l,h}}}{\sqrt{2} k v_{\mathrm{l,h}}}. \tag{9}$$

$Z(\zeta)$ is the plasma dispersion function (Fried and Conte, 1961), $\lambda_{\mathrm{D}j} = (T_j/4\pi n_j Z_j^2 e^2)^{1/2}$ is the Debye length of species j, $\Gamma_0(b_{\mathrm{e}}) = I_0(b_{\mathrm{e}})\exp(-b_{\mathrm{e}})$ with I_0 being the modified Bessel function of 0 order, and $b_{\mathrm{e}} = k_\perp^2 \rho_{\mathrm{e}}^2$, where $\rho_{\mathrm{e}} = v_{\mathrm{e}}/\Omega_{\mathrm{e}}$ is the electron gyroradius. Because the dynamics of the dust is negligible on the time scale of instability, we take $\chi_{\mathrm{d}} \approx 0$.

We consider the ion-acoustic instability of the 'fast' wave driven by an electron current along $\mathbf{B}$. Since the fast wave has phase speed in the regime $v_{\mathrm{e}} > \omega/k \gg v_{\mathrm{l}}$ (see e.g., D'Angelo et al., 1966; Tuszewski and Gary, 2003), this requires $u_{0\mathrm{e}} \gg v_{\mathrm{l}}$. In the negative ion plasma we are considering, there is also the possibility that light ions drifting relative to heavy ions with speed $\sim v_{\mathrm{l}}$ could excite 'slow' ion-acoustic waves, which was considered by D'Angelo (2004). However, from (3) the ratio $u_{0\mathrm{e}}/u_{0\mathrm{l}} \sim (m_{\mathrm{l}}\nu_{\mathrm{l}}/m_{\mathrm{e}}\nu_{\mathrm{e}})$; since the latter quantity is typically $\gg 1$, the critical electron drift for the fast wave instability would generally occur at a smaller electric field E_0. In the following, we confine our attention to the regime where $u_{0\mathrm{l}} \ll \omega/k$, and set both $u_{0\mathrm{l}}$ and $u_{0\mathrm{h}}$ equal to zero for simplicity.

2.1. Analytical results

We give analytic results for the following case. We consider the kinetic regime for the electrons, with $u_{0\mathrm{e}} \ll v_{\mathrm{e}}$, and with both ω and $\nu_{\mathrm{e}} \ll k_z v_{\mathrm{e}}$. We also consider the small electron Larmor radius limit, with $b_{\mathrm{e}} \ll 1$. In this case, the electron susceptibility (6) becomes

$$\chi_{\mathrm{e}} \approx \frac{1}{k^2 \lambda_{\mathrm{De}}^2}\left[1 + \mathrm{i}\sqrt{\frac{\pi}{2}}\, \frac{\omega - k_z u_{0\mathrm{e}}}{k_z v_{\mathrm{e}}} \left(1 + \sqrt{\frac{\pi}{2}} \frac{\nu_{\mathrm{e}}}{k_z v_{\mathrm{e}}}\right)\right]. \tag{10}$$

For the ions, we consider the phase velocity regime where both ζ_{l} and ζ_{h} are both $\gg 1$, where Landau damping is negligibly small. Thus from (7), we have approximately for the ion susceptibilities

$$\chi_{\mathrm{l,h}} \approx -\frac{\omega_{\mathrm{pl,h}}^2}{\omega(\omega + \mathrm{i}\nu_{\mathrm{l,h}})}, \tag{11}$$

where ω_{pl}, ω_{ph} are the plasma frequencies of the light and heavy ions, respectively.

Using the above expressions for the susceptibilities, we solve Eq. (5) for the real and imaginary parts of the frequency, taking $\omega = \omega_{\mathrm{r}} + \mathrm{i}\gamma$, with $|\gamma| \ll \omega_{\mathrm{r}}$. This gives the real frequency

$$\omega_{\mathrm{r}}^2 \approx k^2 \frac{\varepsilon_{\mathrm{h}} T_{\mathrm{e}}}{m_{\mathrm{h}}} \left[1 + \frac{\delta}{\varepsilon_{\mathrm{h}}} M_{\mathrm{r}}\right] (1 + k^2 \lambda_{\mathrm{De}}^2)^{-1}, \tag{12}$$

while the imaginary part of ω is given by

$$\frac{\gamma}{\omega_{\mathrm{r}}} \approx \sqrt{\frac{\pi}{8}} \frac{1}{(1 + k^2 \lambda_{\mathrm{De}}^2)} \left(\frac{u_{0\mathrm{e}}}{v_{\mathrm{e}}} - \frac{\omega_{\mathrm{r}}}{k_z v_{\mathrm{e}}}\right) \left[1 + \sqrt{\frac{\pi}{2}} \frac{\nu_{\mathrm{e}}}{k_z v_{\mathrm{e}}}\right] - \frac{(\nu_{\mathrm{h}} + \nu_{\mathrm{l}}(\delta/\varepsilon_{\mathrm{h}}) M_{\mathrm{r}})}{2\omega_{\mathrm{r}}(1 + (\delta/\varepsilon_{\mathrm{h}}) M_{\mathrm{r}})}. \tag{13}$$

From (12) it can be seen that in a plasma with both ε_{h} and $\delta \gg 1$, the phase speed of the fast wave is much larger than the ion thermal speeds, so ion Landau damping is small. It can also be seen from (12) that for fixed $\varepsilon_{\mathrm{h}} = n_{\mathrm{h}}/n_{\mathrm{e}}$, the frequency decreases as $\delta = n_{\mathrm{l}}/n_{\mathrm{e}}$ decreases, that is, as the charge density of positively charged dust increases (see Eq. (2)). The opposite trend occurs when the dust is negatively charged; the frequency increases as the charge density of negatively charged dust increases. In (13), the first term is the driving term for the instability, requiring that the electron drift speed $u_{0\mathrm{e}} >$ the parallel phase speed of the wave, ω_{r}/k_z. When collisional damping (last term in [13]) is negligible, the critical drift would decrease as δ decreases. However, when collisional damping becomes important, the critical drift can increase as δ decreases, because ω_{r} decreases which can increase the last term in (13).

2.2. Numerical results

In this section we show solutions of (5) for a laboratory plasma and a space application.

2.2.1. Laboratory plasma

We consider parameters that may be representative of laboratory negative ion plasmas containing positively charged dust. Using values based on those given in Kim and Merlino (2006), we consider a plasma in which the light ions are singly ionized potassium K^+ and the heavy ions are SF_6. Thus the ratio of the heavy ion to light ion mass is $M_{\mathrm{r}} \approx \frac{146}{39} \approx 3.74$. We assume that the electron temperature is $T_{\mathrm{e}} \sim 0.2\,\mathrm{eV}$, and that $T_{\mathrm{e}} \sim T_{\mathrm{l}}$ and $T_{\mathrm{e}} \sim 8T_{\mathrm{h}}$ (i.e., the temperature of the heavy ions is $\sim$ room temperature). The background neutral molecules are assumed to be primarily SF_6, and the background gas pressure is taken to be $\sim 1\,\mathrm{mtorr}$ (background neutral density $n_{\mathrm{n}} \sim 1 \times 10^{13}\,\mathrm{cm}^{-3}$). The heavy ion density is taken to be $n_{\mathrm{h}} \sim 2 \times 10^9\,\mathrm{cm}^{-3}$, and the plasma is immersed in a magnetic field of strength $B \sim 0.3\,\mathrm{T}$. The cross section for collisions of electrons with SF_6 at these energies can range from about 10^{-15} to $8 \times 10^{-15}\,\mathrm{cm}^2$ (Ferch et al., 1982); because we have not been able to find data for light or heavy ion collision cross sections with SF_6, we use a nominal value of $5 \times 10^{-15}\,\mathrm{cm}^2$ for all three collision cross sections with neutrals. Using the above parameters, we estimate the collision rates with neutrals and the Coulomb collision rates as follows: $\nu_{\mathrm{en}} \sim 9.5 \times 10^5\,\mathrm{s}^{-1}$, $\nu_{\mathrm{ln}} \sim 3.5 \times 10^3\,\mathrm{s}^{-1}$, $\nu_{\mathrm{hn}} \sim 6.5 \times 10^2\,\mathrm{s}^{-1}$, $\nu_{\mathrm{Ce}} \sim 1 \times 10^6\,\mathrm{s}^{-1}$, $\nu_{\mathrm{Cl}} \sim 3.5 \times 10^3\,\mathrm{s}^{-1}$, and $\nu_{\mathrm{Ch}} \sim 2 \times 10^4\,\mathrm{s}^{-1}$. The above parameters yield the following dimensionless parameters: $\nu_{\mathrm{e}}/\Omega_{\mathrm{h}} \sim 10$, $\nu_{\mathrm{l}}/\Omega_{\mathrm{h}} \sim 0.03$, $\nu_{\mathrm{h}}/\Omega_{\mathrm{h}} \sim 0.1$, and $\omega_{\mathrm{ph}}/\Omega_{\mathrm{h}} \sim 24$ where $\Omega_{\mathrm{h}} \sim 2 \times 10^5\,\mathrm{s}^{-1}$ is the heavy ion gyrofrequency.

The charge density of the dust enters the calculation via $\varepsilon_{\mathrm{d}} = Z_{\mathrm{d}} n_{\mathrm{d}}/n_{\mathrm{e}}$, which affects $\delta = n_{\mathrm{l}}/n_{\mathrm{e}}$ (see Eq. (2)). In order to have sufficient dust charge density to lead to a significant change of δ, it would be probably be required that ε_{d} be on the order of $\varepsilon_{\mathrm{h}} = n_{\mathrm{h}}/n_{\mathrm{e}}$. This means that n_{d} would have to be substantial, which implies that electron and ion collisions with dust grains could become important, as can be seen from the following example. From Kim and Merlino (2006) we find that when $\delta \sim 500$, dust can be positively charged to a surface potential ϕ_{s} of about 0.1 V. For a grain of radius $R = 5\,\mu\mathrm{m}$, the charge state would then be about $Z_{\mathrm{d}} \sim R\phi_{\mathrm{s}}/e \sim 350$. Suppose that $\varepsilon_{\mathrm{h}} = 1000$. Then in order to have $\delta = 1 + \varepsilon_{\mathrm{h}} - \varepsilon_{\mathrm{d}} \sim 700$, say, this requires $n_{\mathrm{d}} \sim 2 \times 10^6\,\mathrm{cm}^{-3}$ for $5\,\mu\mathrm{m}$ grains. In this case, the rate of electron and ion collisions with dust grains (Eq. (4b)) would be larger than their rate of collisions with neutrals (Eq. (4a)). This can be seen by comparing $\sigma_{j\mathrm{d}} n_{\mathrm{d}}$ with $\sigma_{j\mathrm{n}} n_{\mathrm{n}}$. Using $\sigma_{j\mathrm{d}} \sim \pi R^2$, we have that $(\sigma_{j\mathrm{d}} n_{\mathrm{d}})/(\sigma_{j\mathrm{n}} n_{\mathrm{n}}) \sim 30$ for the above parameters. Thus we also include collisions with dust grains in the lab plasma application.

Fig. 1 shows the frequency and growth rate of the ion-acoustic instability versus $k\lambda_{\mathrm{De}}$ obtained by solving (5) for the following parameters corresponding to the SF_6 plasma discussed above: $M_{\mathrm{r}} = 3.74$, $T_{\mathrm{e}} = T_{\mathrm{l}} = 8T_{\mathrm{h}}$, $\varepsilon_{\mathrm{h}} = 1000$, $\omega_{\mathrm{ph}}/\Omega_{\mathrm{h}} = 24$. We take $k = k_z$. The solid curve corresponds to the case when there is no dust present, with $\delta = \varepsilon_{\mathrm{h}}$, $\nu_{\mathrm{e}}/\Omega_{\mathrm{h}} = 10$, $\nu_{\mathrm{l}}/\Omega_{\mathrm{h}} = 0.03$, and $\nu_{\mathrm{h}}/\Omega_{\mathrm{h}} = 0.1$, and with $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.1$. The dashed curve is for the case when positively charged dust is present, with $R = 5\,\mu\mathrm{m}$, $\phi_{\mathrm{s}} = 0.1\,\mathrm{V}$, and $Z_{\mathrm{d}} \sim 350$, and with $n_{\mathrm{d}} \sim 2 \times 10^6\,\mathrm{cm}^{-3}$, yielding $\varepsilon_{\mathrm{d}} = 300$ and $\delta = 700$. The collision frequencies are much larger than in the previous case without dust, being roughly $\nu_{\mathrm{e}}/\Omega_{\mathrm{h}} = 145$, $\nu_{\mathrm{l}}/\Omega_{\mathrm{h}} = 0.5$, and $\nu_{\mathrm{h}}/\Omega_{\mathrm{h}} = 0.2$. For this dashed curve, $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.1$, but note that this requires a much larger E_0 (by a factor of about 15) than for the case without dust. (The dash-dot line is for the same parameters as the dashed line, but with $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.15$.) It can be seen that growth occurs, but the frequency is reduced from the case when there is no dust present. Thus, it appears that as dust is added to such a plasma, the enhanced collision rates may damp or quench the instability, because electron collisions reduce $u_{0\mathrm{e}}$ while ion

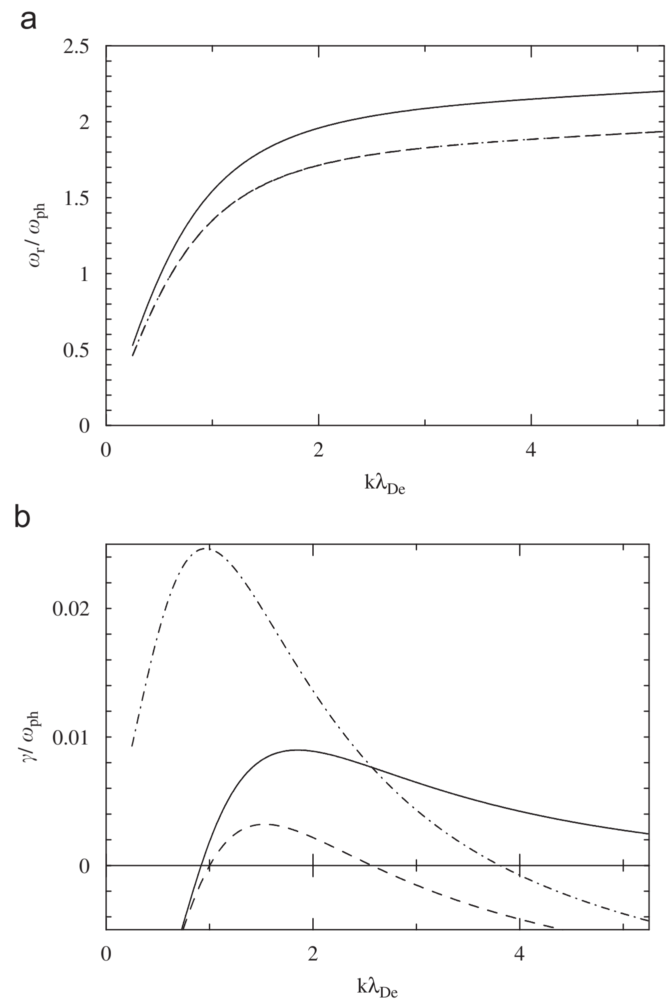

Fig. 1. (a) Real ω_r and (b) imaginary γ parts of ω (normalized to ω_{ph}) versus $k\lambda_{De}$ obtained by solving Eq. (5). Parameters are: $m_l/m_p = 39$, $m_h/m_p = 146$, $\varepsilon_h = 1000$, $T_e = T_l = 8T_h$, $\omega_{ph}/\Omega_h = 24$, and $k = k_z$. The solid curve corresponds to no dust present, with $\varepsilon_d = 0$, and $v_e/\Omega_h = 10$, $v_l/\Omega_h = 0.03$, $v_h/\Omega_h = 0.1$, and $u_{0e}/v_e = 0.1$. The dashed curve corresponds to positively charged dust present, with $\varepsilon_d = 300$, and $v_e/\Omega_h = 145$, $v_l/\Omega_h = 0.5$, $v_h/\Omega_h = 0.2$, and with $u_{0e}/v_e = 0.1$. The dot-dash curve corresponds to the same parameters as the dashed curve, but with $u_{0e}/v_e = 0.15$.

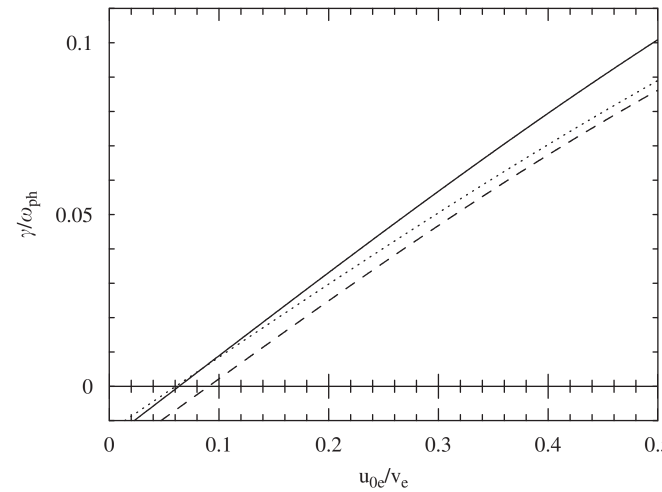

Fig. 2. Imaginary γ parts of ω (normalized to ω_{ph}) versus u_{0e}/v_e obtained by solving Eq. (5), for $k\lambda_{De} = 2$. The solid curve corresponds to the same parameters as in Fig. 1 for no dust present. The other curves correspond to the same parameters as in Fig. 1 for positively charged dust present, except that for the dotted curve, $v_e/\Omega_h = 24$, $v_l/\Omega_h = 0.08$, $v_h/\Omega_h = 0.1$, while for the dashed curve, $v_e/\Omega_h = 145$, $v_l/\Omega_h = 0.5$, $v_h/\Omega_h = 0.2$.

collisions lead to wave damping. But as the electric field E_0 is increased, the instability can turn on again, but at a frequency that is lower than that when no dust is present, if the dust is positively charged. Note that if the dust were negatively charged, the frequency would be larger than that when no dust is present (see Eq. (12)). This suggests a possible diagnostic for the presence of positively charged dust, as well as a diagnostic for the effect of ion–dust collisions.

Fig. 2 shows the critical electron drift to excite a wave with wavelength $\lambda = \pi\lambda_{De}$ in a plasma with the same parameters considered in the previous paragraph (note $\lambda_{De}\sim 0.24$ cm), but for various values of dust grain size and density. For fixed ε_d, the critical drifts would decrease as the grain size decreases, because the ion–dust collision rate scales as $R^2 n_d$ while ε_d scales as Rn_d. We assume the same parameters as above with $\varepsilon_h = 1000$ and $n_h \approx 2\times10^9\,\mathrm{cm^{-3}}$, and positively charged dust with dust surface potential $\phi_s = 0.1$ V and concentration $\varepsilon_d = 300$. The wave frequency is about $2\omega_{ph}$ when no dust is present, and about $1.7\omega_{ph}$ when dust is present. The curves correspond to the following dust parameters: $R = 0.5\,\mu$m and $n_d = 2\times10^7\,\mathrm{cm^{-3}}$ (dotted line), $R = 5\,\mu$m and $n_d = 2\times10^6\,\mathrm{cm^{-3}}$ (dash line), and no dust (solid line). The ratio u_{0e}/v_e can be related to the magnitude of E_0 for this set of plasma parameters as $u_{0e}/v_e \sim 4(\Omega_h/v_e)E_0$, where E_0 is in $\mathrm{V\,m^{-1}}$. Thus the critical electric field strength corresponding to the curves in Fig. 2 is $E_0\sim0.16\,\mathrm{V\,m^{-1}}$ for the case when no dust is present, $E_0\sim0.4\,\mathrm{V\,m^{-1}}$ for the $0.5\,\mu$m grain case, and $E_0\sim3.3\,\mathrm{V\,m^{-1}}$ for the $5\,\mu$m grain case.

2.2.2. Space application

Recently, Rapp et al. (2005) suggested that the presence of a substantial density of negative ions may play a role in explaining their observations of positively charged dust in the Earth's mesosphere between about 80 and 90 km. Their onboard plasma measurements (electrons and positive ions) in fact show that there were large quantities of negative ions present. Rapp et al. (2005) suggest that the presence of heavy negative ions, corresponding perhaps to sub-nm size negatively charged dust grains, could lead to the positive charging of larger nm size ($\sim$2 nm) grains. Specifically, Rapp et al. (2005) find that the presence of negative ions with mass >300 amu in sufficient concentration, $\varepsilon_h > 40$, could explain the observed positive nanoparticle charge. The dust particles that Rapp et al. (2005) refer to are the 'meteoric smoke particles' that are thought to result from meteor ablation and subsequent recondensation and coagulation (Hunten et al., 1980; Rosinski and Snow, 1961).

There could be a substantial density of sub-nm size meteoric dust in the upper mesosphere as well, according to calculations of Hunten et al. (1980). Although there have been scarce observations of dust in this region, recently an observation of meteoric dust and a meteoric contrail at altitude ~93 km has been reported by Kelley et al. (1998). It may be of interest to consider the conditions under which the instability discussed in this paper could be excited in the upper mesosphere, because if such irregularities can occur they could affect radar scattering. In the case we consider below, the negative ions correspond to a population of sub-nm size negatively charged meteoric dust, in analogy with the suggestion by Rapp et al. (2005) mentioned previously. It should be noted that D'Angelo (2005) has considered the effect of massive charged dust on the excitation of ion-acoustic waves in polar mesosphere summer echo (PMSE) regions, using a fluid analysis.

We consider some nominal parameters for a dusty region at an altitude of about 95 km, where the neutral density is $n_{\mathrm{n}} \sim 1 \times 10^{13}\,\mathrm{cm}^{-3}$, the temperatures $T_{\mathrm{e}} \sim T_{\mathrm{l}} \sim T_{\mathrm{n}} \sim 200\,\mathrm{K}$, and the light ion mass $m_{\mathrm{l}} \sim 28 m_{\mathrm{p}}$ (where m_{p} is the proton mass). We assume that a nighttime dusty meteor trail, which has expanded to a radius of ~10 m and length ~10 km, has ion density $n_{\mathrm{l}} \sim 2 \times 10^{4}\,\mathrm{cm}^{-3}$ which is about an order of magnitude larger than background. (For example, this might correspond to a meteor of mass $\sim 10^{-3}$ g with initial line density of $\sim 10^{13}-10^{14}\,\mathrm{m}^{-1}$ (see Hughes, 1978) that has expanded for approximately a few seconds, assuming a diffusion coefficient of about $\sim 10\,\mathrm{m}^{2}\,\mathrm{s}^{-1}$ (see Pellinen-Wannberg and Wannberg, 1996)). We assume there is a population of sub-nm grains in the trail of radius $R \sim 0.3-0.4$ nm, mass $\sim 300 m_{\mathrm{p}}$ (assuming a mass density of $\sim 3\,\mathrm{g\,cm}^{-3}$), and number density $n_{\mathrm{h}} > n_{\mathrm{l}}$. It should be noted that a density $n_{\mathrm{h}} \sim n_{\mathrm{l}}$ would be larger (by several times to an order of magnitude) than that estimated by Hunten et al. (1980) for the steady state distribution of sub-nm meteoric smoke particles at this altitude. More recent calculations by Megner et al. (2006) indicate that the density of meteoric smoke could be larger (or smaller) than the estimates of Hunten et al. (1980) dependent upon a wide range of parameters such as the meteoric input, the particle microphysics, and atmospheric factors. At any rate, if we assume that the sub-nm dust is freshly created in the trail, we estimate the mass of the meteor as 2×10^{-3} g for dust density as high as $n_{\mathrm{h}} \sim 1 \times 10^{6}\,\mathrm{cm}^{-3}$. (For example, this latter value appears to be $\lesssim$ the density of sub-nm dust in the trail of a meteor of mass ~0.01 g after a time of a few seconds, as given in Rosinski and Snow [1961].) This corresponds to the upper mass range of the numerous radar meteors (Hughes, 1978; Ceplecha et al., 1998). We neglect larger nm sized dust grains which take time to grow (Rosinski and Snow, 1961), and take $\varepsilon_{\mathrm{d}} = 0$ in the following.

We assume that some of the sub-nm grains are charged to a negative charge state of unity, providing a population of heavy 'negative ions' with $n_{\mathrm{h}} \sim n_{\mathrm{l}}$. For $B \sim 0.5$ G, the negative ion gyrofrequency is $\Omega_{\mathrm{h}} \sim 17\,\mathrm{rad\,s}^{-1}$. The collision rates are due primarily to collisions with neutrals: for the heavy ions (i.e., the negatively charged sub-nm 'dust') we estimate $\nu_{\mathrm{h}} \sim \pi R^{2} n_{\mathrm{n}} v_{\mathrm{n}} m_{\mathrm{n}}/m_{\mathrm{h}} \sim 100\,\mathrm{s}^{-1}$. For the electrons and positive light ions, we have $\nu_{\mathrm{e}} \sim 8 \times 10^{4}\,\mathrm{s}^{-1}$ and $\nu_{\mathrm{l}} \sim 5 \times 10^{3}\,\mathrm{s}^{-1}$ (Kelley, 1989). Fig. 3 shows solutions of (5) for the above parameters, assuming $k = k_z$ and $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.6$. The curves correspond to 2 values of ε_{h}, namely $\varepsilon_{\mathrm{h}} = 20$ ($\lambda_{\mathrm{De}} \sim 4$ cm) and $\varepsilon_{\mathrm{h}} = 10$ ($\lambda_{\mathrm{De}} \sim 3$ cm). As can be seen, growth (at rate $\sim 2 \times 10^{3}\,\mathrm{s}^{-1}$) occurs in the wavelength range $\lambda \sim$ tens of cm to a meter, so VHF/UHF radar could Bragg scatter from such waves.

The parallel electric field corresponding to $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.6$ is about $20\,\mathrm{mV\,m}^{-1}$. Observations of vertical electric fields of much larger magnitude ($\sim 1\,\mathrm{V\,m}^{-1}$) in the vicinity of noctilucent clouds and PMSE have been reported (Zadorozhny, 2001); the latter paper explains this on the basis of a reduction in conductivity due to electrons (and ions) attaching to dust grains. However, there is controversy about the measurements (see Holzworth et al., 2001). On the other hand, observations of smaller electric fields on the

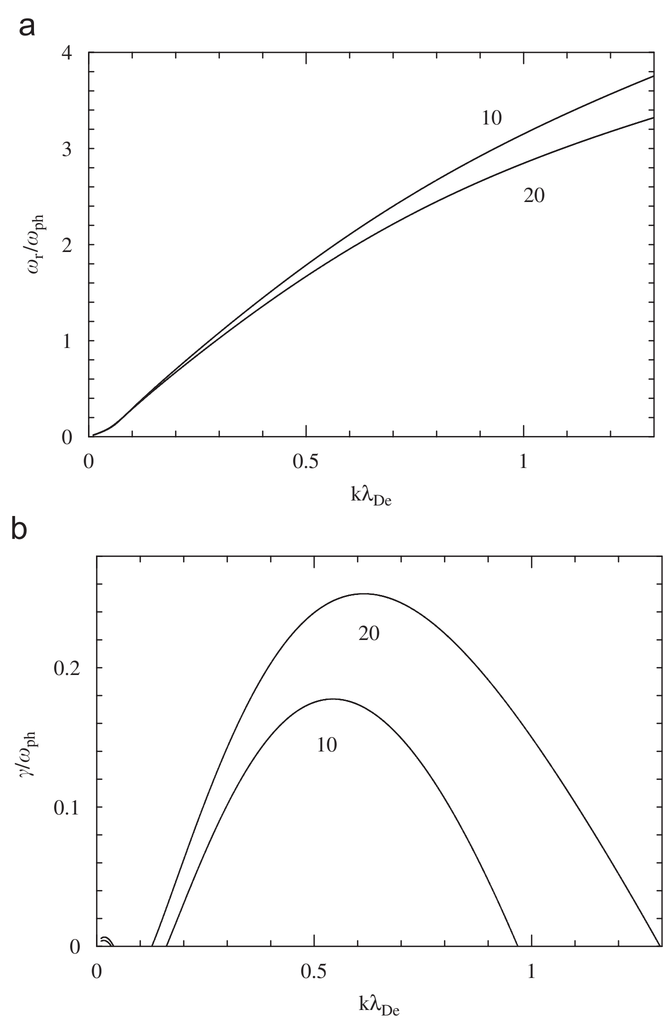

Fig. 3. (a) Real ω_{r} and (b) imaginary γ parts of ω (normalized to ω_{ph}) versus $k\lambda_{\mathrm{De}}$ obtained by solving Eq. (5). Parameters are: $m_{\mathrm{l}}/m_{\mathrm{p}} = 28$, $m_{\mathrm{h}}/m_{\mathrm{p}} = 300$, $T_{\mathrm{e}} = T_{\mathrm{l}} = T_{\mathrm{h}}$, $\omega_{\mathrm{pl}}/\Omega_{\mathrm{h}} = 2350$, $v_{\mathrm{e}}/\Omega_{\mathrm{h}} = 5 \times 10^{3}$, $v_{\mathrm{l}}/\Omega_{\mathrm{h}} = 290$, $v_{\mathrm{h}}/\Omega_{\mathrm{h}} = 6$, and $u_{0\mathrm{e}}/v_{\mathrm{e}} = 0.6$. Here $k = k_z$. The curves are labeled by the values of ε_{h}.

order of a few tens of $\mathrm{mV\,m^{-1}}$ in PMSE during a rocket experiment have been reported (Holzworth et al., 2001). The question of course remains if such fields could occur in dusty regions at these higher altitudes. If this instability could occur, however, what is particularly intriguing is that the ion-acoustic waves could in principle be excited both along and obliquely to the magnetic field. Radar scattering from such waves would thus not have strong aspect sensitivity; it would be interesting to see if this instability might apply to observations of enhanced ion-acoustic echoes in meteor trails reported by Pellinen-Wannberg and Wannberg (1996). Of course, the dust parameters we have chosen are speculative. There are many unknowns, such as the charging of sub-nm dust. Although it has long been thought that dust is formed in meteor trails, there is as yet scarce experimental evidence of the presence of dust in meteor trails, though studies have recently been appearing in this area (e.g., Kelley et al., 1998, 2003; Kelley, 2004). Perhaps the presence of ion-acoustic echoes in the VHF/UHF range from such meteor trail regions might be useful as a diagnostic for the presence of substantial amounts of negatively charged sub-nm dust.

3. Summary

We considered the effect of charged dust on the ion-acoustic instability in a negative ion plasma in which the density of negative ions (which are more massive than the positive ions) is much larger than that of the electrons. We applied the results to both laboratory and space dusty plasmas, motivated by recent work on dusty negative ion plasmas in the laboratory (Kim and Merlino, 2006) and in space (Rapp et al., 2005).

For the laboratory situation, we find that when the electron current in the negative ion plasma is sufficient to drive an ion-acoustic instability, the addition of larger micron size dust may damp the instability due to electron and ion collisions with dust grains. As the electron drift (i.e., the external electric field) is increased, however, the waves can again grow, but with a smaller frequency if the dust is positively charged. This suggests a possible diagnostic for the presence of positively charged dust, as well as a diagnostic for the effect of ion–dust collisions. However, it should be noted that the free energy to drive the instability is relatively small since $n_e/n_h \ll 1$. Thus the level of corresponding wave energy may be small. Nonetheless, the reduction in the frequency of the fast wave due to the presence of positively charged dust might be detected by launching such a wave.

For the space situation, namely, a dusty meteor trail region in the upper mesosphere, we find that if the density of sub-nm size negatively charged 'dust' (i.e., heavy 'negative ions') is comparable to the positive ion density, the ion-acoustic instability may occur for electric field values on the order of $10\,\mathrm{mV\,m^{-1}}$. If such an instability can occur, VHF/UHF radar scattering from ion-acoustic waves (which would not be strongly aspect sensitive) may be a possible diagnostic for the presence of substantial amounts of negatively charged dust at such meteor trail heights.

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