

Ion-acoustic instability in a dusty negative ion plasma

M. Rosenberg^{a,*}, R.L. Merlino^b

^a*Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093, USA*

^b*Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA*

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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.

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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 ~ 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.

*Corresponding author. Tel.: +1 858 5344509.

E-mail address: rosenber@ecepops.ucsd.edu (M. Rosenberg).

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

$$n_l \pm Z_d n_d = n_h + n_e, \quad (1)$$

where n_α is the density of charged species α (the subscript $\alpha = e, l, h, d$ 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

$$\delta = \frac{n_l}{n_e} = 1 + \varepsilon_h \mp \varepsilon_d, \quad (2)$$

where $\varepsilon_h = n_h/n_e$ and $\varepsilon_d = Z_d n_d/n_e$, 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

$$u_{0j} = \frac{eE_0}{m_j v_j}, \quad (3)$$

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

$$v_{jn} \sim \sigma_{jn} n_d v_j, \quad (4a)$$

$$v_{jd} \sim \sigma_{jd} n_d v_j. \quad (4b)$$

Here σ_{jn} , σ_{jd} 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 v_{Cj} , 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 $E_1 \sim \exp(i\mathbf{k} \cdot \mathbf{r} - \omega t)$, 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 $\mathbf{B}$, respectively, is given by (see e.g., Miyamoto, 1989; Kindel

and Kennel, 1971)

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

where

$$\chi_e = \frac{1}{k^2 \lambda_{De}^2} [1 + \zeta_e \Gamma_0(b_e) Z(\zeta_e)] \left[1 + \frac{iv_e}{\sqrt{2} k_z v_e} \Gamma_0(b_e) Z(\zeta_e) \right]^{-1}, \quad (6)$$

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

Here

$$\zeta_e = \frac{\omega - k_z u_{0e} + iv_e}{\sqrt{2} k_z v_e}, \quad (8)$$

$$\zeta_{l,h} = \frac{\omega - \mathbf{k} \cdot \mathbf{u}_{0l,h} + iv_{l,h}}{\sqrt{2} k v_{l,h}}. \quad (9)$$

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

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 $v_e > \omega/k \gg v_l$ (see e.g., D’Angelo et al., 1966; Tuszewski and Gary, 2003), this requires $u_{0e} \gg v_l$. In the negative ion plasma we are considering, there is also the possibility that light ions drifting relative to heavy ions with speed $\sim v_l$ could excite ‘slow’ ion-acoustic waves, which was considered by D’Angelo (2004). However, from (3) the ratio $u_{0e}/u_{0l} \sim (m_l v_l/m_e v_e)$; 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 $u_{0l} \ll \omega/k$, and set both u_{0l} and u_{0h} 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 $u_{0e} \ll v_e$, and with both ω and $v_e \ll k_z v_e$. We also consider the small electron Larmor radius limit, with $b_e \ll 1$. In this case, the electron susceptibility (6) becomes

$$\chi_e \approx \frac{1}{k^2 \lambda_{De}^2} \left[1 + i \sqrt{\frac{\pi}{2}} \frac{\omega - k_z u_{0e}}{k_z v_e} \left(1 + \sqrt{\frac{\pi}{2}} \frac{v_e}{k_z v_e} \right) \right]. \quad (10)$$

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

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