J. Plasma Physics (2006), *vol.* 72, *part* 6, *pp.* 997–1000.
doi:10.1017/S0022377806005460 Printed in the United Kingdom

Instability of a high-frequency wave in irradiated and streaming dusty plasmas

M. K. ISLAM and Y. NAKASHIMA
Plasma Research Center, University of Tsukuba, Ibaraki 305-8577, Japan

(Received 29 July 2005 and accepted 8 December 2005)

Abstract. The instability of a high-frequency wave, such as the Langmuir wave (LW) is studied using a Vlasov-kinetic model in streaming and irradiated dusty plasma with dust charge fluctuation. In irradiated dusty plasma, dust charge fluctuation is considered to be due to the combined effect of LW perturbation and photoelectron emission. It is found that the dust charge fluctuation makes the LW unstable and this instability linearly adds to the Landau effect. Growth rate of the instability of LW is discussed. Discussion is also given to justify the theory and to verify it in the laboratory experiment.

1. Introduction

Dust grains in the range of 10 nm to 100 μm and with a charge of $Q_{\rm d} \sim (10^3$–$10^4)e$ can be immersed both in natural and laboratory plasmas. The dust grains can be charged by absorbing electrons and ions flowing onto their surface. Due to the high mobility of electrons, the grain charge is usually negative. In some special circumstances of dusty plasma, charging due to photoelectron emission, thermonic emission, and secondary emission can be significant and dust grains may become positively charged [1, 2].

The presence of dust grains in plasma can modify the existing plasma modes or may introduce new eigenmodes [3–5]. In a dusty plasma, collective perturbation of plasma parameters can exhibit self-consistent dust charge fluctuations in response to oscillations in the plasma currents flowing into them [6, 7]. The self-consistent dust charge fluctuation usually leads to the damping of the low-frequency mode of the order of ion oscillation frequency [8]. Due to the inertia of ions, ions do not respond at all to the high-frequency Langmuir wave (LW) perturbations. Considering only the LW perturbation on electron–grain current, it was shown that the LW can be unstable due to the dust charge relaxation process [9].

In this paper, a different model of high-frequency dust charge fluctuation is proposed to study its effect on LWs. Fluctuating electron densities $n_{\rm e1}$ are considered to be piled up on a dust grain due to LW perturbation on electron–grain current. The fluctuating dust charge, $Q_{\rm d1}$, is then returned to its equilibrium value through the emission of n_{e1} electrons by the photoelectric effect. The necessary energy of photons for photoelectron emission is given by $h\nu_{\rm p} > e\phi_{\rm w} + e\phi_{\rm d} - 5e^2/8r_{\rm d}$, for $\phi_d > 0$ where $\phi_{\rm d}$, h, $\nu_{\rm p}$, e, $\phi_{\rm w}$, and $r_{\rm d}$ are the potential at dust grain surface, Planck constant, irradiation frequency, charge of electron, grain work function, and radius of dust grain, respectively. The last term is due to the image potential for spherical dust grain and is very small, at most 10^{-3} eV even for a grain radius of around 1 μm

[10]. Hence, to remove the piled up electrons on a grain surface and to not ionize the dust grain, the photon energy must be $e\phi_w > h\nu_p > |e\phi_d|$. Moreover, the flux of irradiation is considered to be sufficient to remove all of the piled up electrons on a dust grain surface through the photoelectric effect. In these limits, we can ignore ϕ_w in the expression of photoelectric current and the photoelectron density, n_e, in this expression can be related with the oscillation of the mode, rather than photon flux (J) and yield of the photoelectrons (Y). In Sec. 2, a detailed description of our dust charge fluctuation model is given. The dispersion relation of the LW is then given in Sec. 3. Section 4 contains the discussions and conclusions on our results. Discussion regarding the justification of the present theory and also the verification of this theory in the laboratory experiment is given in this section.

2. Charging of a dust grain

For the present dust charge fluctuation model as discussed in the introduction, the photoelectric current for a unidirectional photon flux and for $\phi_d > 0$ can be given according to the Einstein relation in photoelectric effect as

$$I_{pe} = I_{pe0} + I_{pe1} = \pi r_d^2 e(n_{e0} + n_{e1})\sqrt{\frac{2(h\nu_p - e\phi_{d0})}{m_e}} \exp\left\{-\frac{e\phi_{d0}}{(h\nu_p - e\phi_{d0})}\right\}, \quad (2.1)$$

where m_e is the mass of an electron. The exponential factor in (2.1) takes into account that the photoelectrons have sufficient energy to overcome the potential barrier of the positively charged grain. The quantities I_{pe0} and I_{pe1} represent the equilibrium and perturbed photoelectron currents, respectively. Comparing (2.1) with other expressions of the photoelectric current for $\phi_d > 0$ and $2\pi r_d/\lambda > 1$ [1, 11], $I_{pe} = \pi r_d^2 eYJ \exp\{-e\phi_{d0}/(h\nu_p - e\phi_{d0})\}$, it is seen that $n_e\sqrt{2(h\nu_p - e\phi_{d0})/m_e}$ of (2.1) is equal to YJ. Here, λ is the wavelength.

If the electron streaming velocity (V_{e0}) becomes much larger than the thermal velocity of electrons (v_{the}), then approximate electron current to positively charged dust grains is given by

$$I_e = I_{e0} + I_{e1} = -\pi r_d^2 e(n_{e0} + n_{e1})V_{e0}\left[1 + \frac{2e\phi_{d0}}{m_e V_{e0}^2}\right]. \quad (2.2)$$

V_{e0} in a dusty plasma may be due to an ambient electric field: In the space plasma system, this electric field may be established due to inhomogeneous distribution of charge carriers [3]. In laboratory plasmas, electric field can be applied externally for better control of plasma and specific purposes. However, $\phi_{d1} = 0$ is considered in (2.1) and (2.2), because this gives the low-frequency damped mode [8].

Quantities I_{pe1} and I_{e1} of (2.1) and (2.2), respectively, are used in the linearized dust charging equation, which is given by

$$\frac{dQ_{d1}}{dt} = I_{pe1} + I_{e1}, \quad Q_{d1} = \frac{i}{\omega}(|I_{pe0}| - |I_{e0}|)\frac{n_{e1}}{n_{e0}}. \quad (2.3)$$

Noting that $I_{i1} = 0$. The LW is so fast that the massive ion and dust do not have time to respond to the oscillation field and may be considered as fixed. Therefore, we have ignored the ion and dust dynamics. At equilibrium $I_{e0} + I_{i0} + I_{pe0} = 0$ and if $|I_{i0}| + |I_{pe0}| > |I_{e0}|$ then the dust grain can be charged positively, $\phi_d > 0$.

https://doi.org/10.1017/S0022377806005460 Published online by Cambridge University Press

3. Dispersion relation

In equilibrium, the dusty plasma is quasi-neutral, i.e. $en_{\mathrm{e}0} = en_{\mathrm{i}0} + Q_{\mathrm{d}0}n_{\mathrm{d}0}$. The dispersion relation of the LW can be obtained from the linearized Poisson's equation, which is given with the value of $Q_{\mathrm{d}1}$ from (2.3) as

$$\phi_1 = -\frac{4\pi e}{K^2}\left[1 - \frac{i}{\omega}(\beta_{\mathrm{p}} - \beta_{\mathrm{e}})\right] n_{\mathrm{e}1}, \tag{3.1}$$

where $\beta_{\mathrm{e}} = (I_{\mathrm{e}0}/e)(n_{\mathrm{d}0}/n_{\mathrm{e}0}) = [1+2e\phi_{\mathrm{d}0}/(m_{\mathrm{e}}V_{\mathrm{e}0}^2)]\pi r_{\mathrm{d}}^2 n_{\mathrm{d}0}V_{\mathrm{e}0}$, $\beta_{\mathrm{p}} = (I_{\mathrm{pe}0}/e)\cdot(n_{\mathrm{d}0}/n_{\mathrm{e}0}) = \pi r_{\mathrm{d}}^2 n_{\mathrm{d}0} v_{\mathrm{pe}}$, $v_{\mathrm{pe}} = \sqrt{2(h\nu_{\mathrm{p}} - e\phi_{\mathrm{d}0})/m_{\mathrm{e}}}\exp\{-e\phi_{\mathrm{d}0}/(h\nu_{\mathrm{p}} - e\phi_{\mathrm{d}0})\}$, and K is the wave number. The $i\beta_{\mathrm{e}}$ and $i\beta_{\mathrm{p}}$ terms arise through coupling to dust charge fluctuations. The coupling parameter β_{e} is like an effective collision frequency of the streaming electrons with the dust grains. On the other hand, β_{p} is the effective detachment frequency of photoelectrons from the dust grains.

When the equilibrium distribution function of an electron is described by drifting Maxwellians

$$f_{\mathrm{e}0} = \frac{n_{\mathrm{e}0}}{\sqrt{\pi}v_{\mathrm{the}}}\exp\left\{-\frac{(v_{\mathrm{e}} - V_{\mathrm{e}0})^2}{v_{\mathrm{the}}^2}\right\}, \tag{3.2}$$

then according to the Vlasov-kinetic model, the perturbed density of electron can be obtained from [12]

$$n_{\mathrm{e}1} = -\frac{e\phi_1}{Km_{\mathrm{e}}}\frac{n_{\mathrm{e}0}}{v_{\mathrm{the}}^2}Z'(\zeta), \tag{3.3}$$

where Z is the dispersion function of argument $\zeta = \overline{\omega}/Kv_{\mathrm{the}}$, $v_{\mathrm{the}} = \sqrt{2k_{\mathrm{B}}T_{\mathrm{e}}/m_{\mathrm{e}}}$, k_{B} is the Boltzmann constant, and $\overline{\omega} = \omega - KV_{\mathrm{e}0}$ is the Doppler shifted frequency. The prime on Z indicates its derivative with respect to its argument. In the limit $\zeta \gg 1$ or $\overline{\omega} \gg Kv_{\mathrm{the}}$, (3.3) becomes

$$n_{\mathrm{e}1} = -K^2\frac{en_{\mathrm{e}0}}{m_{\mathrm{e}}}\left[\frac{1}{\overline{\omega}^2} + \frac{3}{2}\frac{K^2v_{\mathrm{the}}^2}{\overline{\omega}^4} - 2i\sqrt{\pi}\frac{\overline{\omega}}{K^3v_{\mathrm{the}}^3}\exp\left\{-\left(\frac{\overline{\omega}}{Kv_{\mathrm{the}}}\right)^2\right\}\right]\phi_1. \tag{3.4}$$

The dispersion relation of the Langmuir wave is then obtained from (3.1) using the value of $n_{\mathrm{e}1}$ from (3.4) as

$$\begin{aligned}\overline{\omega}^2 = {}& \omega_{\mathrm{pe}}^2\left(1 + \frac{3}{2}\frac{K^2v_{\mathrm{the}}^2}{\overline{\omega}^2}\right) - 2i\sqrt{\pi}\frac{\omega_{\mathrm{pe}}^2\overline{\omega}^3}{K^3v_{\mathrm{the}}^3}\exp\left\{-\left(\frac{\overline{\omega}}{Kv_{\mathrm{the}}}\right)^2\right\}\\ & - i\frac{\omega_{\mathrm{pe}}^2}{\omega}\left(1 + \frac{3}{2}\frac{K^2v_{\mathrm{the}}^2}{\overline{\omega}^2}\right)(\beta_{\mathrm{p}} - \beta_{\mathrm{e}}),\end{aligned} \tag{3.5}$$

where the electron plasma frequency $\omega_{\mathrm{pe}} = \sqrt{4\pi n_{\mathrm{e}0}e^2/m_{\mathrm{e}}}$. In the limit $\overline{\omega} \gg Kv_{\mathrm{the}}$, we obtain the real part of the LW and the growth rate of the wave as, respectively,

$$\begin{aligned}\overline{\omega} &= \sqrt{\omega_{\mathrm{pe}}^2 + \frac{3}{2}K^2v_{\mathrm{the}}^2}\\ \gamma &= -2\sqrt{\pi}\frac{\omega_{\mathrm{pe}}^2\overline{\omega}^2}{K^3v_{\mathrm{the}}^3}\exp\left\{-\left(\frac{\overline{\omega}}{Kv_{\mathrm{the}}}\right)^2\right\} - \pi r_{\mathrm{d}}^2 n_{\mathrm{d}0}\left[v_{\mathrm{pe}} - V_{\mathrm{e}0}\left(1 + \frac{2e\phi_{\mathrm{d}0}}{m_eV_{\mathrm{e}0}^2}\right)\right]\frac{\overline{\omega}}{\omega}.\end{aligned} \tag{3.6}$$

The first term of γ represents the Landau effect. The second and third terms represent the dust charge fluctuation effect.

https://doi.org/10.1017/S0022377806005460 Published online by Cambridge University Press

4. Discussion and conclusions

In the limit $\omega/K > V_{e0}$, only the third term of γ in (3.6) gives the instability of the LW. A similar instability of the LW was obtained in the case of $V_{e0} = 0$ [9], where it was explained through the dust charge relaxation process. However, time scale of this relaxation process is longer than that of the LW. Therefore, this instability is perhaps due to the absorption of perturbed electrons by a dust grain, i.e. comparatively fewer electrons that remain in the plasma must have to move faster under the influence of the Coulomb force to keep the charge neutrality of the plasma. In the limit $\omega/K < V_{e0}$, the first and second terms of γ in (3.6) give the instability of the LW. The first term gives the usual Landau instability [12]. Instability due to second term indicates that the desorbed photoelectrons from the dust grains give their energy to the LW to grow its amplitude with time. In the limit $2e\phi_{d0}/(m_e V_{e0}^2) < 1$, the instability of the LW due to the dust charge fluctuation effect is cancelled out when $v_{pe} = V_{e0}$.

In the case without irradiation and in the equilibrium state, the number of electrons residing on a dust grain can be considered as $Z_d \sim 10^3$ for $r_d \sim 10^{-6}$ m. Therefore, the number of electrons on a dust grain is $Z_d/4\pi r_d^2 \sim 10^9$ cm^{-2}. If the photoelectric yield $Y = 0.1$ [1], then to remove around 10^9 electrons per square centimeter on a dust grain, the required photon flux is $J\ (= Z_d/(4\pi r_d^2 Y)) \sim 10^{10}$ photons cm^{-2} s^{-1}. In addition, to remove the piled up electrons on a grain due to LW perturbations, more photon flux is necessary. However, the necessary photon flux from a UV source can be obtained by focusing the radiation.

The photon energy of UV radiation of frequency of around 1000 THz is 4.14 eV. For $Z_d \sim 10^3$, $e = 1.6022 \times 10^{-19}$ C, $\epsilon_0 = 8.8542 \times 10^{-12}$ Fm^{-1}, and $r_d \sim 10^{-6}$ m, the dust grain potential energy, $e\phi_d = Z_d e^2/4\pi\epsilon_0 r_d = 1.4$ eV. Here, ϵ_0 is permittivity of free space. Therefore, UV radiation of frequency around 1000 THz has sufficient energy to remove the piled up electrons on the dust grain surface, but will not ionize with work functions those dust grains larger than 4.14 eV, such as the metals Ag = 4.46 eV, Cu = 4.45 eV, Al = 4.2 eV, etc. [13]. Therefore, our theory can be verified in a laboratory experiment when $e\phi_w > h\nu_p > |e\phi_d|$ and when photon flux is sufficient to remove all of the piled up electrons on a dust grain surface. The present investigation clarifies many physical phenomena related to the high-frequency mode both in irradiated laboratory and natural dusty plasmas.

References

[1] Goertz, C. K. 1989 *Rev. Geophys.* **27**, 271.
[2] Horanyi, M. et al. 1998 *J. Geophys. Res.* **103**, 8575.
[3] Shukla, P. K. 2001 *Phys. Plasmas* **8**, 1791.
[4] Chu, J., Du, J. B. and Lin, I. 1994 *J. Phys. D* **27**, 296.
[5] Barkan, A., D'Angelo, N. and Merlino, R. L. 1996 *Planet. Space Sci.* **44**, 239.
[6] Nakamura, Y., Bailung, H. and Shukla, P. K. 1999 *Phys. Rev. Lett.* **83**, 1602.
[7] Nunomura, S. et al. 1999 *Phys. Rev. Lett.* **83**, 1970.
[8] Jana, M. R., Sen, A. and Kaw, P. K. 1993 *Phys. Rev. E* **48**, 3930.
[9] Ma, J.-X. and Yu, M. Y. 1994 *Phys. Rev. E* **50**, R2431.
[10] Wood, D. M. 1981 *Phys. Rev. Lett.* **46**, 749.
[11] Rosenberg, M. et al. 1996 *IEEE Trans. Plasma Sci.* **24**, 1422.
[12] Stix, T. H. 1992 In: *Waves in Plasma*, p. 199. New York: AIP.
[13] Dekker, A. J. 1952 In: *Solid State Physics*, p. 215. New York: Macmillan.