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Surface waves in strongly irradiated dusty plasmas

K. N. Ostrikov*
Kharkov State University and Scientific Centre for Physical Technologies, 2 Novgorodskaya No. 93, 310145 Kharkov, Ukraine

M. Y. Yu†
Institut für Theoretische Physik I, Ruhr-Universität Bochum, D-44780 Bochum, Germany

L. Stenflo
Department of Plasma Physics, Umeå University, S-90187 Umeå, Sweden

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High-frequency surface waves at the interface between two dusty plasmas subject to radiation are considered. Ultraviolet radiation with energy flux larger than the photoelectric work function of the dust surface causes photoemission of electrons. The dust charge and the overall charge balance of the plasma are thus modified. The dispersion properties of the surface waves are investigated for three parameter regimes distinguished by the charging mechanisms in the two plasmas. It is shown that photoemission can significantly affect the plasma and the surface waves.

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I. INTRODUCTION

Massive dust particles appear naturally in many space and laboratory plasmas [1–5]. They are charged by the microscopic electron and ion currents flowing into them. Due to the much higher mobility of the electrons the dust particles usually acquire a large negative charge in the equilibrium state, which is characterized by the balance of the microscopic electron and ion grain currents [6–8]. Under specific conditions the overall charge on the dust particles can also become positive. Such a situation can occur in the presence of strong electromagnetic radiation or fast electrons. It has been shown that ultraviolet (UV) photon flux with energy sufficient to extract electrons from the grains can affect the electron Debye length and thus the conditions for Coulomb lattice formation [9,10] and the boundary regions of dusty plasmas [11]. *In situ* rocket measurements in the Earth's polar mesosphere also indicate the existence of striated plasma structures with regions of different dust-charge signs [12]. The positive dust particles may be attributed to solar radiation-induced photoemission of electrons from the dust grains [12,13]. If photoemission is strong enough, the potential and charge of the dust particles can become positive. The ions are thus repelled by the dust and the electron grain current is reduced/reversed by the photoelectrons. Such a change of the sign of the dust particles can greatly modify the properties of the plasma. In particular, in a plasma with positive dust particles, the electron density would be larger than that of the ions, and waves in the plasma could be strongly affected.

In this paper we investigate the effect of photoemission on the steady state and thus the dispersion properties of surface waves (SWs) at the interface between two dusty plasmas with different dust (and thus electron and ion) concentrations. Such an interface can appear if a part of a dusty plasma is irradiated by strong UV light, as what might occur in the laboratory, the Earth's ionosphere, the planetary rings, and interstellar dust clouds near bright stars [1]. It is shown that because of the effect of the strong radiation on the steady-state of the plasmas, the surface waves at the interface can behave very differently from that of radiation-free plasmas.

II. FORMULATION

For simplicity we consider the interface between two homogeneous dusty plasmas. Our model structure consists of two distinct plasma regions. One or both of the regions is homogeneously irradiated by UV light, and the dust particles can be either negatively or positively charged, depending on the intensity of the radiation. For definitiveness, we assume that the UV light in region 1 ($x<0$) is absent or weaker than that in region 2 ($x>0$). One may thus imagine that the UV radiation enters the plasma from region 2 and is weakened by absorption and scattering (by the dust and plasma particles) before reaching region 1. The size of the transition region between the two plasmas is assumed to be much smaller than any of the relevant space scales. This is equivalent to the commonly used assumption of a sharp interface [14]. Stable discontinuous structures with fairly sharp interfaces have often been observed in space and laboratory dusty plasmas [1,15].

The SW eigenfrequency ω of the electron SWs is much larger than the characteristic rates of ion and dust motion, so that the latter can be treated as immobile in the wave field. The average charge of the dust particles is assumed to be constant for a given UV flux intensity, and charge relaxation [16] in the wave field is neglected. Electrons and ions lost to the dust grains are assumed to be compensated by ionization of the neutrals or diffusion. Charge neutrality is assumed to

*Present address: School of Science, Nanyang Technological University, 469 Bukit Timah Rd., 259756 Singapore.

†Author to whom correspondence should be addressed. Electronic address: yu@tp1.ruhr-uni-bochum.de

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be valid in both plasma regions, that is, $-en_{ej}+en_{ij}\pm e|Z_{dj}|n_{dj}=0$, where $j=1,2$, $e>0$ is the electronic charge, n_{ej}, n_{ij}, n_{dj}, and Z_{dj} are the equilibrium electron, ion, and dust densities, and the dust charge number in region j, respectively.

The electromagnetic fields of the SWs are obtained from the standard linearized hydrodynamic and Maxwell equations

$$\partial_t n_{ej}+\nabla\cdot(n_{ej}\mathbf{v}_{ej})=0, \tag{1}$$

$$\partial_t \mathbf{v}_{ej}+\nu_{ej}\mathbf{v}_{ej}=-(e/m_e)\mathbf{E}_j, \tag{2}$$

$$\nabla\times\mathbf{E}_j=-(1/c)\partial_t\mathbf{B}_j, \tag{3}$$

$$\nabla\times\mathbf{B}_j=(1/c)\partial_t\mathbf{E}_j-(4\pi/c)en_{ej}\mathbf{v}_{ej}, \tag{4}$$

where $\mathbf{v}_{ej}$, n_{ej}, and ν_{ej} are the fluid velocity, density and effective collision frequency of electrons, and $\mathbf{E}_j$ and $\mathbf{B}_j$ are the electric and magnetic fields of the SW.

Depending on the intensity and transparency of the UV flux in the two plasma regions, three distinct cases are possible. Case I: the dust charge remains negative in both regions 1 and 2. This occurs when the intensity of the photoemission current is low. The latter is sufficient to affect the charge of the dust grains in region 2 but not in region 1. Case II: positive dust particles in region 2 and negative ones are in region 1. Here the radiation in region 2 is sufficiently intense to turn the dusts positive, but its action on the dusts in region 1 is absent or weak. Case III: the radiation is so strong that the dust charge in both regions 1 and 2 are positive. In the following section we analyze the currents flowing into and off a dust grain and derive the equations for the equilibrium dust charge and electron density which govern the SW dispersion relation.

III. THE STEADY STATES

We consider the charge balance in both plasma regions for cases I–III. For case I the dust particles are negative in both regions 1 and 2. The equilibrium charge neutrality conditions for regions 1 and 2 are $n_{e1}=n_{i1}-|Z_{d1}|n_{d1}$ and $n_{e2}=n_{i2}-|Z_{d2}|n_{d2}$, respectively. We assume that the UV radiation affects the dust charge in region 2, where the charge on the dusts is determined by balancing the electron, ion, and photoemission currents. One obtains [1,9]

$$\left(\frac{8T_{e2}}{\pi m_e}\right)^{1/2}(n_{i2}-|Z_{d2}|n_{d2})\exp\left(-\frac{e^2|Z_{d2}|}{a_2T_{e2}}\right)=\left(\frac{8T_{i2}}{\pi m_i}\right)^{1/2}n_{i2}\left(1+\frac{e^2|Z_{d2}|}{a_2T_{i2}}\right)+\frac{I_{\rm ph}Y}{e\pi a_2^2}\left(1+\frac{e^2|Z_{d2}|}{a_2T_{pe2}}\right), \tag{5}$$

where a_2, T_{e2}, T_{i2}, and T_{pe2} are the dust radius, electron, ion, and photoelectron temperatures, respectively. The latter is in general different from that of the plasma electrons, but rapid thermalization can occur if electron-electron collisions are frequent. In Eq. (5) $I_{\rm ph}$ is the UV photon flux, and Y is the yield of photoelectrons. The value of Y is near unity for metals and near 0.1 for dielectrics [1]. The quantity $I_{\rm ph}/\pi a_2^2$ is the photon flux per unit area of the dust grain, and

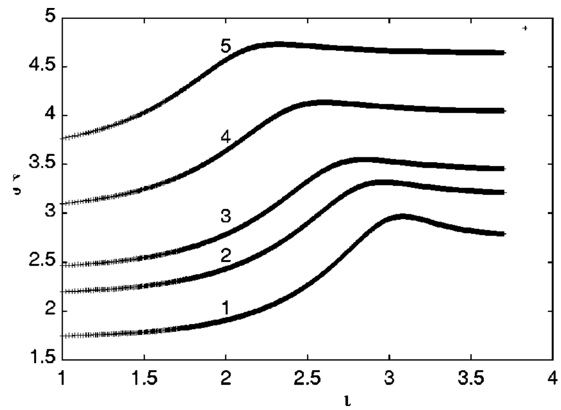

FIG. 1. Dependence of the magnitude of a negative dust charge on the intensity of the UV flux. Here $\zeta=\log(|Z_{d2}|)$, $\iota=-\log(I_{\rm ph})$, $T_e=0.15$ eV, $T_{pe}=0.2$ eV, $T_i=0.015$ eV, $n_{i2}=5\times10^5$ cm^{-3}, $n_{d2}=5\times10^2$ cm^{-3}. Curves 1–5 correspond to the following values of the dust size a_2 and yield of photoelectrons Y: 0.5 μm and 0.2, 1 μm and 0.2, 2 μm and 0.2, 3 μm and 0.25, and 5 μm and 0.25, respectively.

$YI_{\rm ph}/e\pi a_2^2$ is the charge extracted by the UV photons from a unit surface area of the dust grain per second. The dependence of the magnitude of the dust charge on the intensity of the UV flux is presented in Fig. 1 for typical (averaged) parameters [17] of the lower ionospheric F region. Curves 1–5 correspond to different values of the dust size and photoelectron yield.

The equilibrium dust charge in the radiation-free region 1 is determined by a balance between the electron and ion grain currents. One obtains [6]

$$1+\frac{e^2|Z_{d1}|}{a_1T_{i1}}=\left(\frac{T_{e1}m_i}{T_{i1}m_e}\right)^{1/2}\left(1-\frac{|Z_{d1}|n_{d1}}{n_{i1}}\right)\exp\left(-\frac{e^2|Z_{d1}|}{a_1T_{e1}}\right), \tag{6}$$

where a_1, T_{e1}, and T_{i1} are the dust radius, electron, and ion temperatures in region 1, respectively.

For case II, the dust particles in region 2 are driven positive by the UV radiation, and those in region 1 remain negative. We recall that the charging dynamics for positive dust particles is quite different from that for negative ones because of the complete difference in the orbit behavior for both the electrons and ions [7,8,12,16]. Furthermore, we can neglect the ion grain current, as shall be verified later. The balance of the plasma and photoelectron currents yields

$$\left(\frac{8T_{e2}}{\pi m_e}\right)^{1/2}(n_{i2}+|Z_{d2}|n_{d2})\left(1+\frac{e^2|Z_{d2}|}{a_2T_{e2}}\right)=\frac{I_{\rm ph}Y}{e\pi a_2^2}\exp\left(-\frac{e^2|Z_{d2}|}{a_2T_{pe2}}\right), \tag{7}$$

which allows one to determine the (positive) dust charge eZ_{d2}. Note that when the dust charge is positive, the photoelectric current is greatly reduced because of the action of the attracting positive potential of the grain on the released photoelectrons. The dependence of the dust charge on the UV flux is given in Fig. 2 for the same ionospheric parameters as

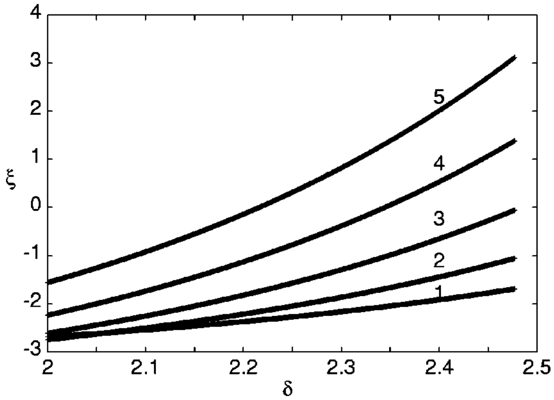

FIG. 2. The same as in Fig. 1, but for positive dust grains. Here $\xi=\log(Z_{d2})$, $\delta=\log(I_{\rm ph})$, and the other parameters are the same as in Fig. 1. Curves 1–5 are plotted for the a_2 and Y values: 0.1 μm and 0.15, 0.2 μm and 0.3, 0.3 μm and 0.35, 0.5 μm and 0.35, and 1 μm and 0.4, respectively.

in Fig. 1. It is clear that the magnitude of the dust charge is much lower than that for negatively charged dusts.

As soon as the grain becomes positive, the ion grain current becomes much smaller because of electrostatic repulsion. From the marginal condition $Z_{d2}\approx 0$, it is easy to verify from Eqs. (5) and (7) that $|I_i|/|I_e|\sim(T_i m_e/T_e m_i)^{1/2}\ll 1$, so that the ion grain current is indeed negligible. The equilibrium ion density is given by

$$n_{i2}=\frac{I_{\rm ph}^{\rm thr}Y}{e\pi a_2^2}\left(\frac{8T_{e2}}{\pi m_e}\right)^{-1/2}, \tag{8}$$

where $I_{\rm ph}^{\rm thr}$ is the threshold UV photon flux for the production of positively charged dust grains. Expression Eq. (8) also allows one to estimate the UV photon flux necessary for the complete neutralization of the dust grains in region 2. In Fig. 3 we show the dependence of the threshold photoelectron current on the average dust size for the parameters (ion density, plasma, and photoelectron temperature, and the photoelectron yield per incident photon) corresponding to the

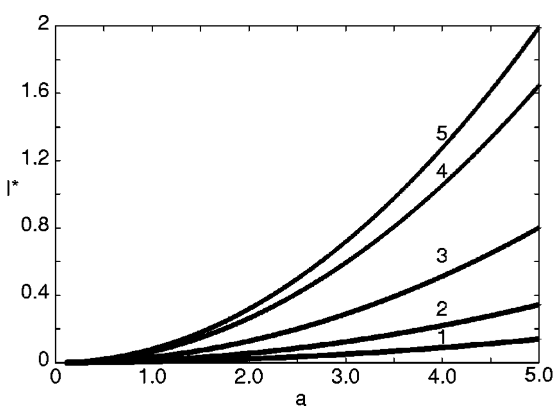

FIG. 3. Dependence of the threshold photoelectron current $I^*=I_{\rm ph}^{\rm thr}$ (in statamperes) on the average dust size a (in micrometers) for different parameters of the ionospheric layer. Curves 1–5 correspond to the T_e, n_{i2}, and Y values: 0.15 eV, 3×10^4 cm^{-3}, and 0.2; 0.2 eV, 8×10^4 cm^{-3}, and 0.25; 0.25 eV, 2×10^5 cm^{-3}, and 0.3; 0.3 eV, 5×10^5 cm^{-3}, and 0.4; and 0.35 eV, 7×10^5 cm^{-3}, and 0.5, respectively.

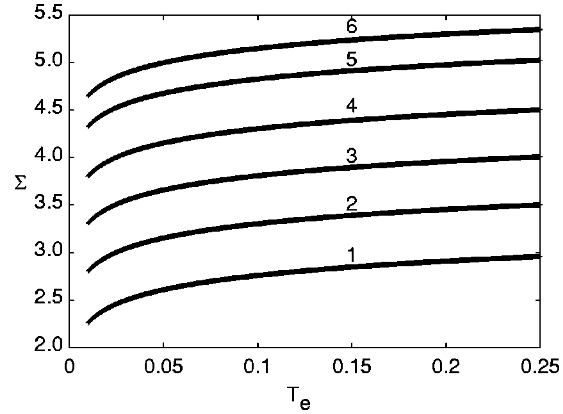

FIG. 4. Dependence of the threshold UV photon flux per unit surface area of the dust grain $\Sigma=I_{\rm ph}^{\rm thr}/\pi a^2$ (in photons per cm^2) on the electron temperature for different parameters of the ionospheric layer. Curves 1–6 correspond to the n_{i2} and Y values: 1×10^4 cm^{-3} and 0.35; 3×10^4 cm^{-3} and 0.3; 8×10^4 cm^{-3} and 0.25; 2×10^5 cm^{-3} and 0.2; 5×10^5 cm^{-3} and 0.15; and 7×10^5 cm^{-3} and 0.1, respectively.

ionospheric layer in our example. In Fig. 4 the dependence of the threshold photon flux per unit area of the dust surface on the electron temperature is shown. From Fig. 3 we see that more intense radiation is necessary to neutralize larger dust grains.

When the dust charge in region 1 is unaffected by the radiation we have $n_{e1}=n_{i1}-|Z_{d1}|n_{d1}$ and $n_{e2}=n_{i2}+|Z_{d2}|n_{d2}$. On the other hand, if the dust particles in region 1 are affected by the radiation but still negative, the equilibrium dust charge Z_{d2} is determined from Eq. (7). The corresponding quantity Z_{d1} can be obtained from Eq. (5). The electron densities n_{e1} and n_{e2} can easily be obtained from the corresponding charge neutrality conditions.

In case III the dust particles are positive in both regions 1 and 2; Eq. (7) (with appropriate modification of the indices 1 or 2) can be used to determine Z_{d1} and Z_{d2}. In this case the electron densities in the two regions are $n_{e1}=n_{i1}+|Z_{d1}|n_{d1}$ and $n_{e2}=n_{i2}+|Z_{d2}|n_{d2}$, respectively.

The above cases roughly model the different stages of the interaction of UV radiation of increasing intensity with a structured dusty plasma or the different regions of the plasma as the radiation penetrates it with reducing intensity because of absorption and scattering by the dust particles. Different combinations of these cases can also model other situations. For example, both regions can contain negative dust particles but are differently affected by the UV light. In this case the corresponding equations for the equilibrium dust charge can easily be obtained by combining Eqs. (5)–(8).

IV. SURFACE WAVE DISPERSION RELATION

We consider electron SWs propagating at the interface along the z direction. All perturbations in the SW field are assumed to vary like $A(\mathbf{r},t)=A(x)\exp[i(k_z z-\omega t)]$, where k_z is the SW wave number. From the basic equations (1)–(4) with the boundary conditions $B_{y1}=B_{y2}$ and $E_{z1}=E_{z2}$ [14] at the interface $x=0$, we can easily obtain the dispersion equation for the high-frequency SWs,

$$\kappa_1/\epsilon_{p1}+\kappa_2/\epsilon_{p2}=0, \tag{9}$$

where $\kappa_{(1,2)}=[k_z^2-k^2\epsilon_{(p1,p2)}]^{1/2}$ are the inverse skin depths of the SWs in regions 1 and 2, $\epsilon_{pj}=1-\omega_{pj}^2/\omega^2$, $k=\omega/c$, and $\omega_{pj}^2=4\pi e^2 n_{ej}/m_e$. The form of Eq. (9) is the same as that for dust-free plasmas [18] except that all quantities here depend on the dust density as well as the intensity of the UV flux. We have assumed that the characteristic oscillation frequencies are much higher than the collision and photoemission frequencies. From Eq. (9) one obtains the wave number for waves propagating in the positive z direction

$$k_z=k[\epsilon_{p1}\epsilon_{p2}/(\epsilon_{p1}+\epsilon_{p2})]^{1/2}, \tag{10}$$

and the inverse skin depths

$$\kappa_1=k[-\epsilon_{p1}^2/(\epsilon_{p1}+\epsilon_{p2})]^{1/2}, \tag{11}$$

and

$$\kappa_2=k[-\epsilon_{p2}^2/(\epsilon_{p1}+\epsilon_{p2})]^{1/2}, \tag{12}$$

in regions 1 and 2, respectively. From Eqs. (9)–(12) it follows that electron SWs exist in the frequency range $\omega_L<\omega<\omega_U$, where $\omega_L=\min\{\omega_{p1},\omega_{p2}\}$ and $\omega_U=[(\omega_{p1}^2+\omega_{p2}^2)/2]^{1/2}$.

The properties of SWs are now analyzed. First, we consider case I where the dust particles are negatively charged in both regions. The dust particles lose electrons by photoemission, so that both $|Z_{d1}|$ and $|Z_{d2}|$ decrease (compared with the radiation-free case). Since the intensity of the UV radiation is assumed to be higher in region 2 and the dust charge in both regions is negative, the variation of $|Z_{d2}|$ with the flux intensity is larger than that in region 1. To study the modification of the SW dispersion properties as the UV flux intensity increases, we take as reference $I_{\rm ph}=I_{\rm ph}^{(0)}$, say the minimum radiation flux level to be considered. In the following the superscript (0) shall denote evaluation at this reference level. We assume that with this flux level the electron density in region 2 is larger than that in region 1, or

$$n_{i2}-|Z_{d2}|n_{d2}>n_{i1}-|Z_{d1}|n_{d1},$$

where all terms are evaluated for $I_{\rm ph}=I_{\rm ph}^{(0)}$. The dispersion curves for this case are shown in Fig. 5, where the frequency is normalized by $\omega_{p1}^{(0)}$. We see that the wave frequency has a lower as well as an upper bound, which shall be referred to as ω_L and ω_U, respectively. The cutoff frequency ω_L coincides with the plasma frequency ω_{p1} of region 1. Increasing the UV flux intensity results in an increase of ω_L as well as the limiting frequency ω_U, with the change in the latter larger.

For $n_{e2}<n_{e1}$, the cutoff frequency ω_L first coincides with ω_{p2}, as shown in Fig. 6. An increase of $I_{\rm ph}$ leads to a decrease of $|Z_{d2}|$ and a faster increase of $\omega_L=\omega_{p2}$ than that of ω_{p1}. The upper limiting frequency ω_H increases with $I_{\rm ph}$ at a rate comparable to that of ω_L. However, one finds that ω_{p2} becomes larger than ω_{p1} when the magnitude of the dust charge $|Z_{d2}|$ becomes smaller than $|Z_{d2}^{\rm thr}|$, where

$$|Z_{d2}^{\rm thr}|=(n_{i2}-n_{e1}^{\rm thr})/n_{d2}, \tag{13}$$

and the superscript thr denotes evaluation at the threshold $I_{\rm ph}=I_{\rm ph}^{\rm thr}$. Furthermore, when $|Z_{d2}|<|Z_{d2}^{\rm thr}|$, the lower cutoff

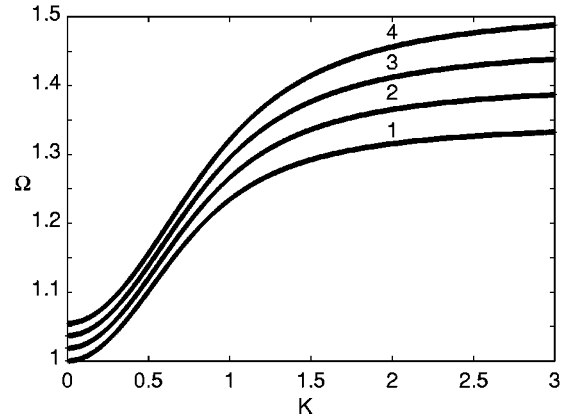

FIG. 5. Dispersion curves of the high-frequency SWs for case I (negative dusts in both regions), where $\Omega=\omega/\omega_{p1}^{(0)}$, and $K=k_z c/\omega_{p1}^{(0)}$ are the normalized frequency and wave number of the SWs. $|Z_{d1}^{(0)}|n_{d1}/n_{i1}=0.2$, $|Z_{d2}^{(0)}|n_{d2}/n_{i2}=0.3$, and $n_{i2}/n_{i1}=3$. Curves 1–4 correspond to the following values of $|Z_{d1}|/|Z_{d1}^{(0)}|$ and $|Z_{d2}|/|Z_{d2}^{(0)}|$: 1 and 1, 0.85 and 0.75, 0.7 and 0.5, and 0.55 and 0.25, respectively.

ω_L is equal to ω_{p1} (curves 3 and 4 in Fig. 6). A further increase of the UV flux intensity results in an increase of both ω_L and ω_U. Note that the threshold can only be reached if $n_{i2}>n_{e1}^{\rm thr}$. From Eq. (13) one can also obtain the threshold value of the UV flux intensity $I_{\rm ph}^{\rm thr}$ provided that $\omega_L=\omega_{p2}$ for $I_{\rm ph}<I_{\rm ph}^{\rm thr}$, and $\omega_L=\omega_{p1}$ for $I_{\rm ph}>I_{\rm ph}^{\rm thr}$. When the effect of the UV flux on the dust charge in region 1 can be neglected (see the discussion in Sec. III), the lower cutoff $\omega_L=\omega_{p1}^{\rm thr}$ is independent of the photon flux intensity.

We now turn our attention to case II where the dust particles in region 2 are positive, and those in region 1 negative. Here the UV irradiation leads to an increase of Z_{d2} and a decrease of $|Z_{d1}|$. Clearly, when the condition (8) as applied to region 2 (i.e., replacing the index 2 by 1) is met, the dust charge in region 1 can be completely neutralized. The effect of the UV flux is also strongest here because of the strong dependence of the electron density on $I_{\rm ph}$. In case I since the UV flux was smaller in region 1, the variation of the magnitude of the dust charge was larger in region 2. However, the present case can be quite different since the variation of the electron density in region 1 (negative dusts) with the UV flux intensity is much more than that in region 2 (positive dust

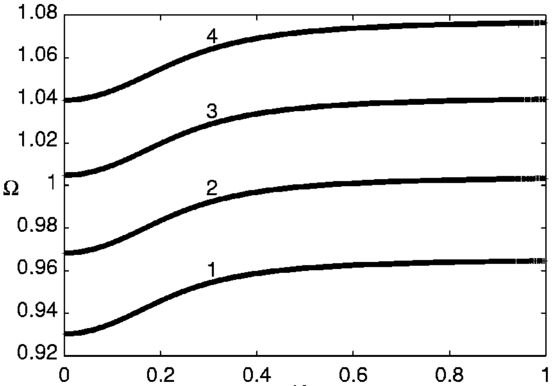

FIG. 6. The same as in Fig. 5, but $|Z_{d1}^{(0)}|n_{d1}/n_{i1}=0.35$, $|Z_{d2}^{(0)}|n_{d2}/n_{i2}=0.25$, and $n_{i2}/n_{i1}=0.75$.

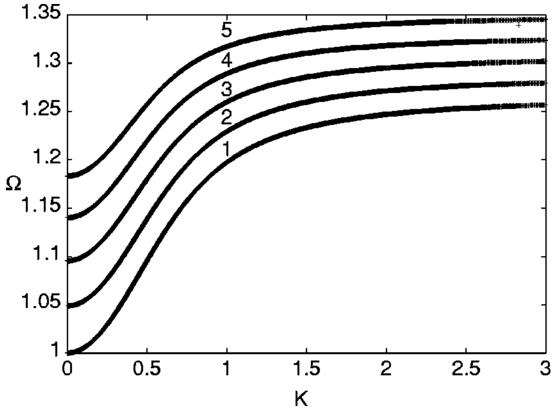

FIG. 7. Dispersion curves for case II (positive dusts in region 2 and negative in region 1). Here $|Z_{d1}^{(0)}|n_{d1}/n_{i1}=0.4$, $|Z_{d2}^{(0)}|n_{d2}/n_{i2}=0.1$, and $n_{i2}/n_{i1}=1.2$. The curves 1–5 correspond to the following values of $|Z_{d1}(I_{\rm ph}^{(1)})|/|Z_{d1}^{(0)}|$ and $|Z_{d2}(I_{\rm ph}^{(1)})|/|Z_{d2}^{(0)}|$: 1 and 1, 0.85 and 1.05, 0.7 and 1.1, 0.55 and 1.15, 0.4 and 1.2, respectively.

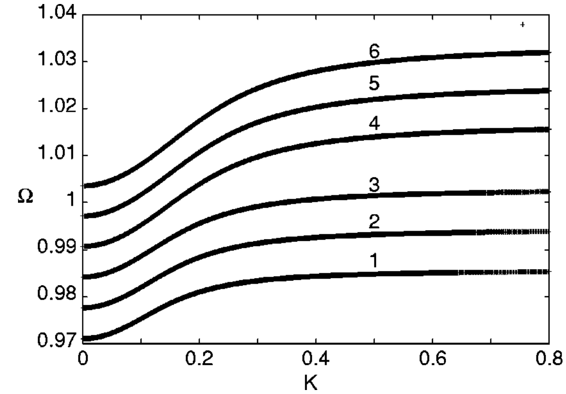

FIG. 8. The same as in Fig. 7. Here $|Z_{d1}^{(0)}|n_{d1}/n_{i1}=0.3$, $|Z_{d2}^{(0)}|n_{d2}/n_{i2}=0.1$, and $n_{i2}/n_{i1}=0.6$. The curves 1–6 correspond to the following values of $|Z_{d1}^{(1)}|/|Z_{d1}^{(0)}|$ and $|Z_{d2}^{(1)})|/|Z_{d2}^{(0)}|$: 1 and 1, 0.95 and 1.15, 0.9 and 1.3, 0.8 and 1.45, 0.75 and 1.6, and 0.6 and 1.75, respectively.

particles). This is because the large positive attractive dust potential in region 2 exponentially reduces the number of the released photoelectrons. Therefore, despite the weaker UV flux in region 1, the variation of the electron density with $I_{\rm ph}$ can under certain conditions be actually larger than that in region 2. Thus two situations are possible: the first is when n_{e2} increases faster with the UV flux than n_{e1}. This also means that the increases of Z_{d2} with the UV flux is faster than the decrease of $|Z_{d1}|$. The second is when the electrostatic interaction (attraction in region 2 and repulsion in region 1) of the dust grains with the photoelectrons prevails over the effect of the UV flux scattering. Here n_{e1} can increase with $I_{\rm ph}$ faster than n_{e2}.

First we assume $n_{e2}>n_{e1}$ at the minimum flux level, that is,

$$n_{i2}+|Z_{d2}|n_{d2}>n_{i1}-|Z_{d1}|n_{d1},$$

where all terms are evaluated at $I_{\rm ph}=I_{\rm ph}^{(0)}$. In this case ω_{p1} is the lower cutoff for the SWs and the dispersion curves are qualitatively similar to that in Fig. 5. If the scattering is strong enough, $|Z_{d2}|$ increases faster than $|Z_{d1}|$ decreases with the radiation flux. This means that $\omega_L=\omega_{p1}$ always remains less than ω_{p2}. Here ω_U also increases faster than ω_L. In fact, if the variation Z_{d1} with the UV flux intensity can be neglected, the lower cutoff is nearly independent of the flux intensity. Otherwise, the increase of $|Z_{d2}|$ is less than the decrease of $|Z_{d1}|$. If the magnitude of the dust charge Z_{d1} (which decreases with $I_{\rm ph}$) exceeds the threshold

$$|Z_{d1}^{\rm thr}|=(n_{i1}-n_{e2}^{\rm thr})/n_{d1},$$

the lower cutoff still coincides with ω_{p1} but approaches ω_{p2} as the flux intensity increases, as shown in Fig. 7. Furthermore, both ω_L and ω_U increase with $I_{\rm ph}$ at the same rate. The threshold can be reached in this case if $n_{i1}>n_{e2}^{\rm thr}$. Further increase of the UV flux leads to a decrease of Z_{d1}, so that $Z_{d1}<Z_{d1}^{\rm thr}$ and one finds $\omega_L=\omega_{p2}$. After the threshold is reached, ω_U and ω_{p1} increase faster than ω_{p2} (see Fig. 7, curves 4 and 5).

We now consider $n_{e2}<n_{e1}$ at the minimum flux level, that is,

$$n_{i2}+|Z_{d2}|n_{d2}<n_{i1}-|Z_{d1}|n_{d1},$$

where all terms are evaluated at $I_{\rm ph}^{(0)}$. This means that $\omega_L=\omega_{p2}$ at $I_{\rm ph}=I_{\rm ph}^{(0)}$. If $|Z_{d2}|$ increases faster than the decrease of $|Z_{d1}|$, an increase of $I_{\rm ph}$ results in a faster rise of ω_L than ω_{p2}, as shown in Fig. 8. If $|Z_{d2}|>|Z_{d2}^{\rm thr}|$, where $|Z_{d2}^{\rm thr}|=(n_{e1}^{\rm thr}-n_{i2})/n_{d2}$, the lower cutoff is equal to ω_{p1}. If, however, the effect of the UV radiation is weaker than that of the electron grain current, $|Z_{d2}|$ rises slower than the decline of $|Z_{d1}|$. The lower cutoff in this case coincides with ω_{p2}. We also note that ω_U rises faster than ω_L for a further increase of $I_{\rm ph}$ (Fig. 9).

Finally, we examine case III where both regions 1 and 2 contain positively charged dust particles. As region 2 is more affected by the UV flux, Z_{d2} increases with the latter more than Z_{d1}. If $n_{e2}<n_{e1}$ at the minimum flux level, that is,

$$n_{i2}+Z_{d2}n_{d2}<n_{i1}+Z_{d1}n_{d1},$$

for $I_{\rm ph}=I_{\rm ph}^{(0)}$, the lower cutoff coincides with ω_{p2}. It increases with $I_{\rm ph}$ faster than ω_{p1}. If Z_{d2} exceeds the threshold

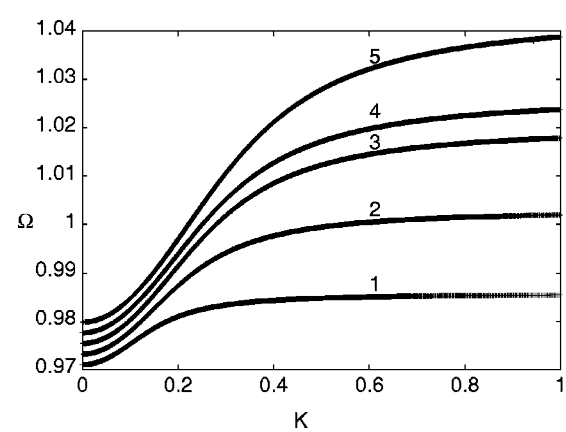

FIG. 9. The same as in Fig. 8. Curves 1–5 correspond to the following values of $|Z_{d1}^{(1)}|/|Z_{d1}^{(0)}|$ and $|Z_{d2}^{(1)}|/|Z_{d2}^{(0)}|$: 1 and 1, 0.85 and 1.05, 0.7 and 1.1, 0.65 and 1.15, and 0.5 and 1.2, respectively.

value $Z_{d2}^{\rm thr}=(n_{e1}^{\rm thr}-n_{i2})/n_{d2}$, one obtains $\omega_L=\omega_{p1}$. To reach the threshold, $n_{e1}^{\rm thr}$ must be larger than n_{i2}. For $Z_{d2}>Z_{d2}^{\rm thr}$ the upper frequency limit increases faster than the lower one. If, however, $n_{e2}<n_{e1}$ at $I_{\rm ph}=I_{\rm ph}^{(0)}$, ω_L would always be equal to ω_{p1}, and ω_U would increase as $I_{\rm ph}$ increases. The dispersion curves in this case are qualitatively similar to that in the case of negative dust particles.

V. DISCUSSION

We have shown that when the dust charge is affected by intense UV radiation, surface waves propagating on the interface between two physically distinct regions of a dusty plasma are modified. In particular, it is shown that when positively charged dusts are created by the radiation, the properties of the equilibrium states of the plasmas and therefore the surface waves can be strongly affected. If the dust charge is negative, the negative surface potential facilitates the release of photoelectrons, and dust charge variation with the radiation flux intensity can be very large. However, as soon as the dust particles become positive, the photoelectrons are hindered from escaping from the dust surface by the much stronger positive potential barrier. Thus a much higher UV flux intensity is necessary to further increase the positive dust charge than that for neutralizing the originally negatively charged dust. For this reason, the magnitude of the charge of a positive dust is for reasonable UV flux intensity much smaller than that of a negative dust particle. It is shown that depending on the degree of dust charge modification by the radiation, the upper and lower limits in the surface wave frequency are strongly modified.

We have assumed that the densities of the plasma particles remain unaffected by the radiation during the oscillations. In reality the intense UV flux can also act on the neutral atoms/molecules and thus affect the ionization-recombination balance in the plasma. In this case the resulting variation of the particle densities must also be included. Such effective particle sources and sinks, as well as diffusion (which are of the same order), can appear as dissipation and lead to damping of the surface waves. Furthermore, to avoid unnecessary complication in the algebra, we have not explicitly taken into account possible differences in the mass, size, and type of the dusts in the adjoining plasma regions. However, such cases can readily be incorporated in our results by redefining the plasma parameters appropriately.

Radiation plays important roles in determining the composition and properties of many space and cosmic plasmas. The present work shows that by significantly modifying the steady state, the radiation can greatly affect the propagation of surface waves in the plasma. In particular, our results should be useful in the diagnostics of the Earth's ionospheric regions with distinct night and daytime behaviors. They may be relevant to regions affected by ozone holes, as the enhanced UV radiation would greatly increase plasma production in the lower ionosphere which would otherwise be very weakly ionized. The results can also be applied in the studies of interstellar dust clouds subject to strong radiation from the nearby stars. The sharp boundary in our model would then be realized when a part of the plasma is shaded from the radiation by another cloud or an arm of the same cloud.

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