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Comment on "Dispersion relation for the dust ionization and dust acoustic waves in the gas discharge complex plasma" [Phys. Plasmas 29, 073701 (2022)]

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Recently, the results of experiments on the excitation of compressional waves in complex plasmas in the Plasmakristall-4 (PK-4) facility on the International Space Station[1] were published.[2] The experiments showed excitation of the wave mode, which is about an order of magnitude faster than the conventional dust acoustic mode. To explain this result, in Ref. 2, a new dust wave mode termed "dust ionization wave" (DIW) in which the modulation of dust density is coupled to the localized ionization balance was suggested. This mode has a substantially larger wavelength compared to the conventional acoustic mode, which makes it observable only in the elongated geometry of PK-4. Reference 3 presented a more extended version of the DIW theory compared to that of Ref. 2. Despite the elegance of the idea, I believe that the experimental data available from Ref. 2 do not give enough confidence to state that ionization effects play the role in the propagation of compressional waves in complex plasmas. In my argumentation below, I use the notation of Ref. 3.

First of all, neither Ref. 2 nor Ref. 3 clearly states that the theoretical dispersion relation of the DIW and the experimentally measured dispersion relation have qualitatively different shapes: In the $(\omega; k)$ plane, the theoretical curve [Eq. (23) of Ref. 2 and Figs. 1 and 2 of Ref. 3)] is concave, whereas the experimental curve (Fig. 10 of Ref. 2) is convex. Reference 3 attributes the differences in the theoretical and experimental curves to uncertainty in the ionization and recombination coefficients as well as in the finite size and inhomogeneity of the microparticle suspension in which the waves propagate. These issues could certainly affect the quantitative details of the dispersion relation, e.g., difference in the cutoff frequencies discussed in Ref. 3. It is, however, not clear how they could qualitatively affect the shape of the dispersion curve. Reference 3 contains no physical argumentation about it.

The author of Ref. 3 correctly states that at excitation frequencies below the frequency cutoff, the microparticle suspension will perform only forced sloshing oscillations. Therefore, *in the vicinity of the frequency cutoff*, the experimental dispersion curve may indeed change its shape due to the transition from DIW to sloshing oscillations. This transition should be accompanied by the inflection and maximum of the dispersion curve [if represented in $(\omega; k)$ plane], which is not observed in the experiment.

In Ref. 3, it is stated that although the experimental frequency cutoff is about two to three times lower than the theoretical one, the wavenumber cutoffs are in good agreement in experiment and theory, respectively. However, I would like to note that, in Ref. 3, the calculation of the wavenumber cutoff for comparison with the experiment is associated with certain arbitrariness in the choice of plasma parameters most of which are summarized in Table I. Since n_{d0} is the only quantity, which is reliably measured in the experiment (Fig. 4 of Ref. 2), its variation from Ref. 2 to 3 is strange. In Ref. 2, it is clearly stated that the wave propagation was observed for x between 4 and 15 mm, where $n_{d0} \simeq 1.34 \times 10^5$ cm^{-3}. According to Fig. 5 of Ref. 3, k_d weekly depends on n_{d0} only for $n_{d0} = (7 \pm 2) \times 10^4$ cm^{-3}. However, when changing n_{d0} from 7×10^4 to 1.34×10^5 cm^{-3}, k_d will drop several times if all other parameters remain unchanged. Parameter n_{e0} is certainly much worse experimentally defined compared to n_{d0}, but its variation from one paper to another for the same experimental conditions by a factor of 20 requires comments. Also, the value of $n_{i0} = 1 \times 10^8$ cm^{-3} in Ref. 3 seems to be too small. The Langmuir probe measurements in the (dust-free) dc discharge of PK-4 (Fig. 4 of Ref. 4) suggest several times larger value, which would lead to lower values of H and, again, smaller k_d. Since k_d depends on both n_{d0} and n_{e0} stating its coincidence or noncoincidence with the

TABLE I. Comparison of experimental and calculated parameters in Refs. 2 and 3.

Parameter	Ref. 2	Ref. 3
p_{gas} (Pa)	11.5	11.5
T_{e} (eV)	3	3
$2a$ (cm)	3.38×10^{-4}	3.38×10^{-4}
Z	1200	1000
n_{d0} (cm^{-3})	1.34×10^{5}	7×10^{4}
n_{e0} (cm^{-3})	6×10^{8}	3×10^{7}[a]
H	0.27	2.4
k_{d} (cm^{-1})	3.6	2.02

[a]Calculated using the quasineutrality condition $n_{\mathrm{i0}} = n_{\mathrm{e0}} + Zn_{\mathrm{d0}}$.

experimental value can only be claimed after establishing the reliable values of plasma parameters.

The dispersion relation obtained in Ref. 3 contains two branches corresponding to acoustic and ionization waves, respectively. However, in the experiment, only one branch with the velocity much higher than that of the acoustic waves is observed. In Ref. 3, it is explained by the fact that the acoustic mode has about an order of magnitude larger damping length compared to the ionization mode. In fact, the possibility of observing a wave mode is related to the possibility of observing the evolution of its phase which, in its turn, is related not to the absolute value of its damping length, but rather to the ratio of its damping length to its wavelength. For the DIW branch, this ratio can be estimated as $k_{\mathrm{d}}\delta l/2\pi \approx 0.3$ (taking $k_{\mathrm{d}} = 2.02$ cm^{-1}). The reduction of k_{d} would lead to the corresponding reduction of this ratio. For the acoustic branch, this ratio can be estimated as $\omega_0\delta l/2\pi c_{\mathrm{a}} \approx 0.5$ for $\omega_0/2\pi = 10$ Hz. In this sense, both branches are overdamped and DIW branch is subject to even somewhat stronger damping than the acoustic branch.

The last issue that I would like to address concerns the $An'_{\mathrm{d}}/n_{\mathrm{d0}}$ term in Eq. (5) of Ref. 3. Introduction of this term leads to the reduction of the damping of acoustic waves and, as stated in Ref. 3, can even lead to the instability. It is, therefore, important to understand how realistic this instability mechanism is. As it is correctly stated in Sec. II of Ref. 3, in the absence of gravity, the two main forces acting on the microparticles are electrostatic and ion drag forces, both depending on the electric field. The total time-averaged force per unit volume of the microparticle suspension is given by Eq. (1) of Ref. 3. The next statement that, in equilibrium, this force vanishes due to the vanishing expression in square parentheses [Eq. (2) of Ref. 3] is, however, questionable. On the one hand, as noted in Ref. 3, the inhomogeneity of the microparticle suspension suggests the presence of ambipolar-like time-averaged electric field. However, on the other hand, presence of the ambipolar-like electric field contradicts the idea of localized ionization balance which, in fact, is assumed to be the physical basis of the DIW mode. Also, it was shown, e.g., in Ref. 5 that the electrostatic and ion drag forces acting on a microparticle can be balanced at non-zero electric field values only if the ion density exceeds certain threshold. According to Fig. 11 of Ref. 5, this threshold lies at $n_{\mathrm{i0}} \sim 10^{9}$ cm^{-3}, which is one order of magnitude larger than the value of n_{i0} supposed in Ref. 3. It could be more realistic that the equilibrium in Eq. (1) of Ref. 3 is provided by the condition $\mathbf{E} = \mathbf{0}$. It would be very advantageous to perform the first-principles modeling of the microparticle suspension under the conditions of Ref. 2 to clarify the situation.

In conclusion, there is only one undoubtful experimental observation in favor of the DIW hypothesis of the anomaly fast compressional dust wave mode experimentally observed in Ref. 2, namely, the relatively high phase velocity of the wave. This is certainly not enough to completely accept this hypothesis. Further experimental and theoretical efforts are required to shed the light onto the nature of this wave mode. Not only the wave dispersion, but also mechanisms leading to the reduction of the wave damping are awaiting to be clarified.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

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