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Influence of the Nature of Charge Fluctuations on Dust Cluster Oscillation Spectrum

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Abstract

Results of numerical modelling of the cluster mode spectra are presented. Particular attention has been paid for the influence of the nature of the charge fluctuations on the mode spectra of small clusters. We demonstrate that one of the main effects related to the charge fluctuations, a splitting of the spectrum lines, reveals different patterns depending on the nature of the fluctuations. The analysis of the influence of the charge fluctuations on the normal mode spectra of dust clusters demonstrates the mode splitting related with the nature and the variance of the fluctuations.

Crystals containing a small number of micrometer-size dust particles are called dust clusters or Coulomb clusters [1]. In a recent study [2], the first analysis of the normal modes in Coulomb clusters with fluctuating charges was performed for correlated fluctuations. This analysis demonstrated the normal mode splitting related with the variance of the fluctuations. It was reported that the fundamental pure rotational modes are the most affected by the charge fluctuations while the least affected were the pure translational modes.

Here, we present results of numerical modeling of the normal mode spectra in small Coulomb clusters. Our mode-spectral analysis is performed for 2D clusters of N = 3; 7 particles with fluctuating charges. It is based on the model detailed in [2] which is further developed to allow consideration correlated as well as non-correlated charge fluctuations. The model assumes that three forces determine dynamics of dust particles in the considered Coulomb clusters. The confining force is due to a parabolic potential well, the Coulomb repulsion force is related to fluctuating charges, and friction forces particles to slow down. The total energy of the cluster in the equilibrium state is calculated according to the standard expression [3]:

$$E = \frac{1}{2}\gamma_r \sum_{i=1}^{N} r_i^2 + Q^2 \sum_{i>j}^{N} \frac{1}{r_{ij}} \exp\left(-\frac{r_{ij}}{\lambda_D}\right)$$

We normalize the distances by $r_0 = (2Q^2/\gamma_r)^{1/3}$ which relates the particle interaction to the strength of the radial confinement. The force acting on each particle is derived from F = ΔU where U is the potential energy of the system. The charge on each dust particle fluctuates randomly about an equilibrium value. The fluctuations can be set up either correlated (for all particles) or uncorrelated. The mode spectra of N = 3, 7 clusters are shown in Fig. 1. As can be seen from this figure, the mode spectra of clusters with correlated fluctuations significantly differ from the mode spectra of clusters with uncorrelated fluctuations. The changes in the spectra increase with the increasing variance: namely, there is splitting of the spectral lines of the modes and shift of the mode frequencies. The correlated and uncorrelated spectra vary differently: in general, the modes in the correlated spectra exhibit large frequency shifts, while spitting of degenerated modes is the feature of the uncorrelated spectra, see Fig. 1

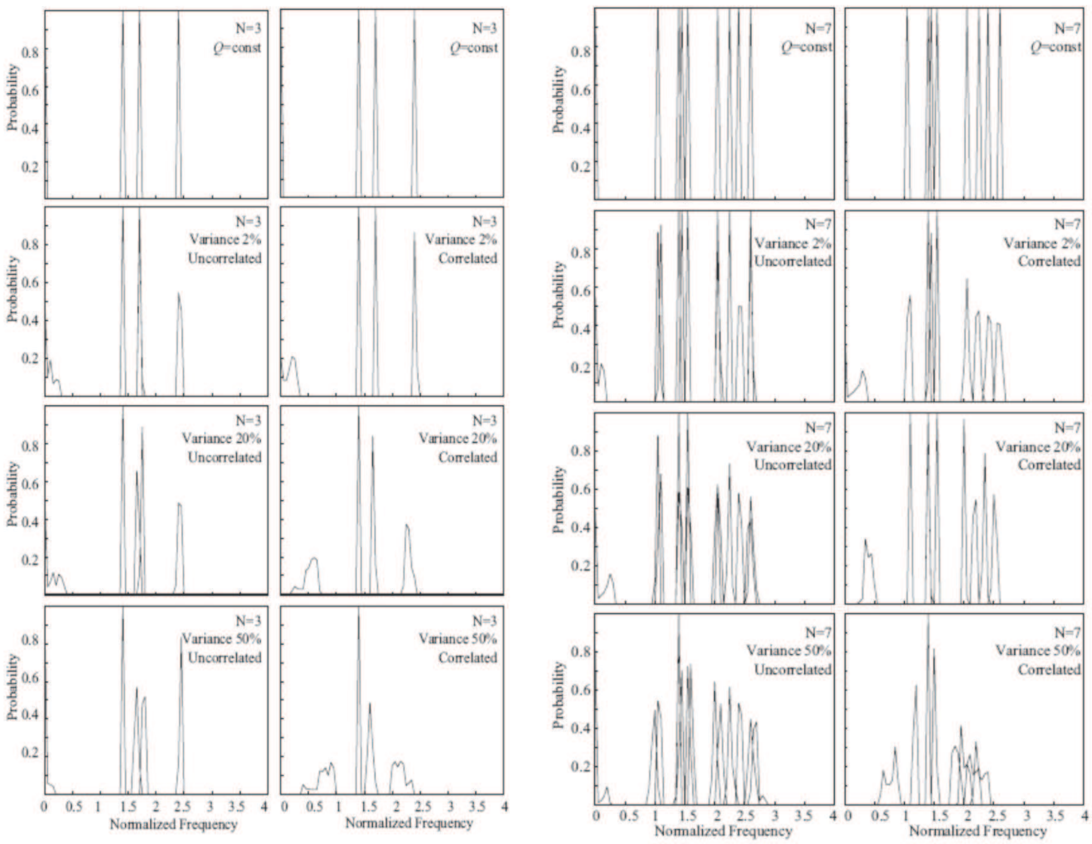

Figure 1. Mode spectra for cluster with no charge fluctuations as well as uncorrelated and correlated dust charge fluctuations with different variances.

It is clear that the modes are split/shifted according to the mode number and the weight of the shear and compressional parts in their oscillation pattern. The pure rotational modes (with the maximum shear component) and the breathing modes with the maximum compression component are the most affected. The pure translational modes appear to be the most stable irrespectively on the nature of fluctuations. It is found that the distinctive signature of the correlated fluctuations is a significant shift of the zero-frequency mode and an overall narrowing of the spectrum band.

The most influenced mode is the first one, which is split for both correlated and uncorrelated fluctuations but shifted only for the correlated spectra, when the charge fluctuation variance is increased to 50%. This splitting shows that the pure rotational mode with the highest shear component is the most sensitive to the correlated charge fluctuations. It can be explained by the fact that correlated fluctuations induce the coherent radial motion of dust particles leading to the shifting oscillation frequency, while the uncorrelated fluctuations induce random particle motions leading to the spreading of the mode.

The least influenced are the modes 4 and 5 corresponding to pure translations. The degenerated modes 2 and 3 are shifted in the correlated spectra and split in the uncorrelated spectra. We note that the shear value for these modes exceeds significantly their compressional value and therefore the modes are shifted towards higher frequencies with the increasing charge variance. Other modes are split/shifted according to the mode number and the weight of the shear and compressional parts in their oscillation pattern. For the correlated spectra, the high frequency modes are shifted towards lower frequencies leading to the narrowing spectral band of all modes.

Based on the results obtained, we are able to analyze the experimental mode spectra of 2D Coulomb clusters reported by Melzer [4]. The presented spectrum for N=3 cluster shows significant shift of the zero frequency mode (the mode 2 in the author's notation [4]), the highest frequency mode (the mode 1 in the author's notation) is also shifted. This clearly indicates that the charge fluctuations are correlated. The overall measured frequency band is lower than the one predicted for the constant charge case, which is the signature of the correlated spectra. However, we cannot claim the pure correlated nature of the charge fluctuations. The splitting of the modes 4 and 5 indicates the presence of a non-correlated fluctuation component. In our simulations, we never obtained splitting of the translational modes 2 and 3, but it was observed in the experiments [4]. This can be attributed to the fact that the translational modes depend only on the effect of the confining force on the particles; in our model the particle-confining well interaction was assumed in the simplest parabolic form not taking into account details of the interaction. Since in experiments the confinement is usually realized as an electrostatic confinement, for future simulations we plan to further extend the model by inclusion of electrostatic effects as well as non-parabolic terms in the confinement, and the plasma screening.

The possibility to determine the nature of charge fluctuations by analyzing the oscillation spectra is much more convincing when looking at clusters with higher numbers of particles. If we look on the experimental spectra of N = 34 and N = 145 clusters [5], it is easy to see the difference in the position of the zero frequency mode. It is shifted for N = 34 cluster and not shifted for N = 145 cluster. Thus we detect the presence of correlated fluctuations in the case of smaller N = 34 cluster, while there are mostly uncorrelated fluctuations for larger N = 145 cluster. This indicates the opportunity to determine the correlation length by analyzing oscillation spectra of dust clusters with different numbers of particles. To conclude, it was found that the main effects related to the dust charge fluctuations are the splitting/spreading and the shifting of the spectral lines of the oscillation modes. The splitting/spreading and the shifting are proportional to the value of the charge fluctuation variance and the type (correlated/uncorrelated) of the fluctuations. This fact can be very useful as the character of dust charge fluctuations can give us important information on the related correlation length, and, as we see from the current study, this character can be extracted from the analysis of the cluster mode spectra.

Acknowledgements

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