Formation and dissociation of dust molecules in dusty plasma*

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Dust molecules are observed in a dusty plasma experiment. By using measurements with high spatial resolution, the formation and dissociation of the dust molecules are studied. The ion cloud in the wake of an upper dust grain attracts the lower dust grain nearby. When the interparticle distance between the upper dust grain and the lower one is less than a critical value, the two dust grains would form a dust molecule. The upper dust grain always leads the lower one as they travel. When the interparticle distance between them is larger than the critical value, the dust molecule would dissociate.

Keywords: dust plasma, dust molecule

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1. Introduction

Dust plasma is characteristic of micro-sized dust grains immersed in the plasma.[1–5] For typical low temperature gas-discharge experiments, the dust grains are often charged negatively because the electrons in the plasma have much higher thermal velocities than the ions.[6–10] The amount of charge in a dust grain can reach 10^4e, therefore, the grains couple strongly due to their repulsive interaction which is described by the Yukawa potential. Various phenomena such as the dust crystal and the dust soliton have been observed in radio-frequency (rf) and DC gas discharges.

Besides the repulsive interaction between the dust grains, there exists an attractive interaction between them, which plays an important role in some new phenomena such as the alignment of dust grains. A wake region below a dust grain forms when the supersonic ions flow downward across the dust grain. Positive ion space charge is accumulated in the wake of the dust particle by ion focusing.[11–14] The ion cloud attracts negatively-charged dust grains nearby it. By using laser manipulation, Piel *et al.*[15,16] have studied experimentally the attraction between a couple of dust grains in a two-particle system. In this work, we study experimentally the dynamics of dust molecules confined by a glass ring in an rf plasma. The formation and dissociation of the dust molecules are discussed in detail.

2. Experimental setup

The experiments are performed in a vacuum chamber as shown schematically in Fig. 1. The upper electrode is an ITO glass plate and is grounded. The lower electrode is a stainless steel plate which is connected to an rf power at a frequency of 13.56 MHz. The distance between the two electrodes is 100 mm. The discharge gas is argon at a flow rate of 10 sccm. In order to confine the dust grains, a glass ring of 10 mm in height and 13 mm in diameter is placed on the center of the lower electrode. Monodisperse polystyrene microspheres of 23 μm diameter serve as the dust grains. Being injected into the plasma of discharge, the grains would levitate above the lower electrode and close to the ring as shown in Fig. 2.

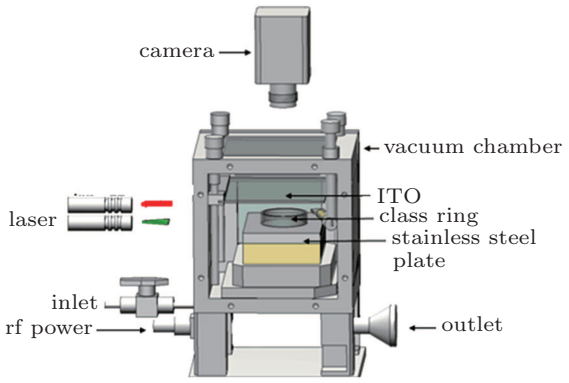


Fig. 1. (color online) Schematic diagram of the experimental setup.

When the grain distribution is dense enough, multilayers of grains would form. The measurement of spatial resolution of the multilayers is realized by two laser sheets set horizontally. The thickness of the laser sheet is about 0.2 mm, which is less than the distance between two layers of grains. Firstly, a red laser sheet is used to illuminate horizontally one layer of grains. One can observe red spots (illuminated grains) clearly from the upper camera. Then a green laser is used to sweep the grains layer by layer. After the two laser sheets overlap, we move the green laser downward continually until another clear layer of green spots appears clearly. Then, we observe two adjacent layers, the red layer is above the green one as

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shown in Fig. 2. We find that a green spot would follow the red spot above it. Thus, we can observe couples of spots from the top view and call them dust molecules. In the following, we will focus on the dynamics of the dust molecules.

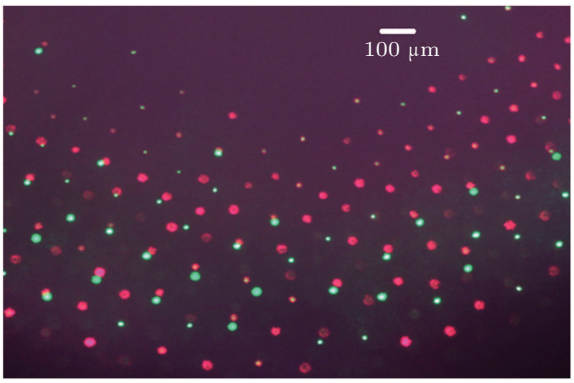


Fig. 2. (color online) Dust molecules. The image is captured from a part of the glass ring (power: 5 W, gas pressure: 70 Pa). The red layer is above the green one.

3. Experimental results and analysis

3.1. The motion of dust molecule

For a couple of dust grains, the green spot (lower) always follows its upper red spot. From the recorded movie, we can obtain the trajectories of the dust molecules. Figure 3 shows the trajectories of a couple of dust grains for a duration of 1.6 s. It can be seen that the two grains get close to each other and follow similar trajectories. The lower (green) grain always lags behind the upper (red) one as shown in Fig. 4. The phase difference is about 0.06 ± 0.02 s between the two trajectories. Therefore, there exists a certain correlation between the two grains.

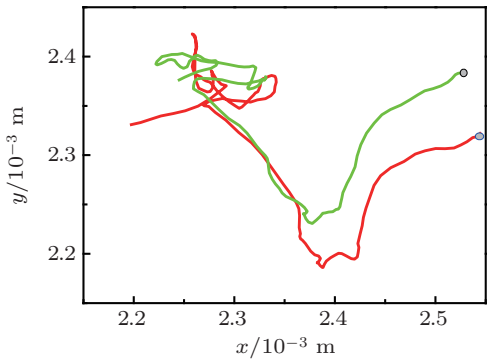


Fig. 3. (color online) Trajectory of a dust molecule for a duration of 1.6 s. The red (green) line represents the trajectory of the red (green) spot, i.e., the upper (lower) grain. The two circles indicate the starting positions of the two grains.

The formation of a dust molecule in plasma originates from the attractive force between the upper and lower grains. This attractive force is related with the ion focus induced by the upper grain, which has been observed by Melzer *et al.*[17] When ions flow downstream of the upper grain, a region (so called wake) with positive space charge appears below this grain. The ion cloud in the wake induced by the upper grain can attract the negatively-charged grain below it. In our experiment, the grains are close to the wall of the glass ring. There exists a horizontal component of the ion flow, which gives rise to a separation of the upper and lower grains in the top view as shown in Fig. 2. This is the origin of the formation of a dust molecule as we observed. The direction of the molecule bond is mainly along the radius of the glass ring due to the ion flow toward the wall of the glass ring. Near the center of the glass ring, ions flow downward to the electrode, therefore, the two grains in a dust molecule seem to be overlapped in the top view as shown in Fig. 2.

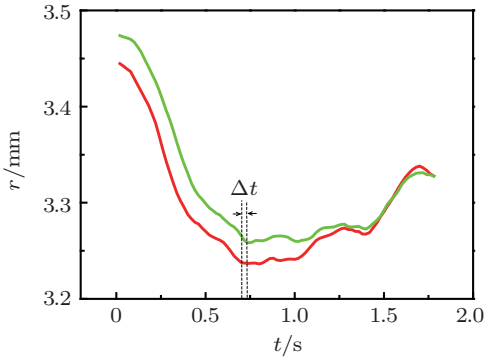


Fig. 4. (color online) Dependance of the positions of the two grains in a dust molecule (Fig. 3) on time. The position is measured from the grain to the center of the glass ring. The red (green) line refers to the red (green) spot, i.e., the upper (lower) grain.

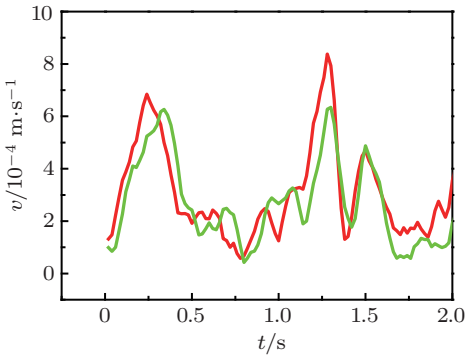


Fig. 5. (color online) Dependence of the velocities of the two dust grains in a dust molecule on time. The red (green) line refers to the red (green) spot, i.e., the upper (lower) grain.

Because the ion cloud in the wake is induced by the ion focus from the upper grain, the upper grain always leads the lower one as they travel. Besides the attraction from the ion cloud, the lower grain also experiences a neutral drag, which leads to a time delay between their trajectories as illustrated in Fig. 4. The upper grain (red line) is in advance of the lower one (green line) by about 0.06 ± 0.02 s as they travel. Figure 5 shows the dependence of the velocity of the dust molecule on the time for a duration of 2 s. It is clear that for the duration of 0–1.6 s, the velocity variations of the two grains are very similar and the phase lag is about 0.06 ± 0.02 s, which is in accordance with Fig. 4. This process corresponds to the translation

of the dust molecule as indicated in Fig. 3. The maximum velocity is about 0.8 mm/s. The velocities vary periodically with a period of about 1 s, which results from the cage effect from the upper grain. After the moment of 1.6 s, the dust molecule settles down near its equilibrium position and undergoes random thermal motion as shown in Fig. 3. The correlation between the two grains still exists, which can be found in the velocity variations in Fig. 5.

The correlation between the two grains in a dust molecule can also be found from the cross correlation function of the velocities of the two grains

$$R(\Delta t) = \frac{1}{N}\sum_{i=0}^{N-1} v_1(i)\, v_2(i+\Delta t).$$

Figure 6 shows the cross correlation function of the velocities in Fig. 5. The first center peak appears at $\Delta t = 0.04$ s which indicates the time delay between the motions of the two grains. The second peak appears at $\Delta t = 0.94$ s which corresponds to the cage period of the upper grain.

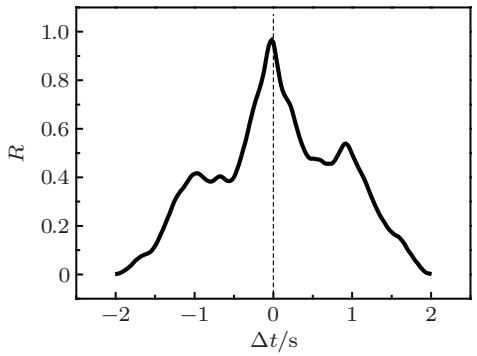


Fig. 6. Cross correlation function of the velocities in Fig. 5.

3.2. Formation and dissociation of dust molecule

Dust grains in the plasma are strongly coupled due to their high electric charge and the couple parameter is about $\Gamma = \frac{Q^2/a}{4\pi\varepsilon_0 k_B T} \approx 32$ ($Q \approx 10600e, a \approx 100$ μm, $k_B T \approx 5$ eV) in our experiment, i.e., the system is in the liquid state. The grains in the upper layer undergo stochastic motion as shown in Figs. 3 and 4. When an upper grain interacts strongly with its neighbor at the same layer, it could be accelerated. The lower grain under this upper grain would follow it as soon as possible. Due to the natural drag to the lower grain, the interparticle distance in the dust molecule increases and the attractive force between them becomes weak. If the natural drag to the lower grain is stronger than the attraction force, the two grains would separate and this dust molecule decomposes. This is shown by the trajectories of the two grains indicated by A and B in Fig. 7. The two dust grains first start as a dust molecule from the positions indicated by the two circles, and then they separate into two isolated grains. Figure 8(a) shows the change of the interparticle distance with time, in which the interparticle distance between grains A and B (indicated by the black line) keeps nearly constant 0.06 mm from 0 to 0.2 s and increases gradually after 0.2 s which illustrates their separation. Therefore, there exists a critical interparticle distance $\Delta r_c = 0.06$ mm beyond which the dust molecule decomposes. Figure 8(b) shows the change of the positions of the grains with time. The grains A and B combine well at the beginning and then separate.

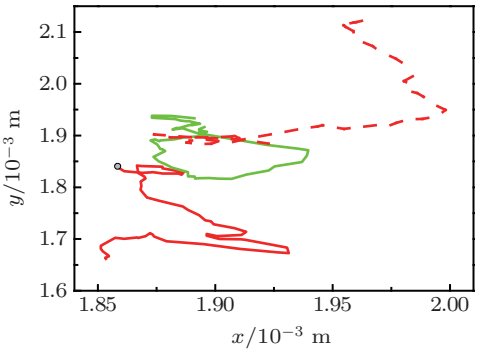


Fig. 7. (color online) Trajectories of three dust grains, which show the formation (B–C) and dissociation (A–B) of dust molecules. The three circles indicate the starting positions of the three grains.

A dust molecule can form when the interparticle distance between an upper grain and a lower grain is less than the critical value. Figure 7 illustrates the formation of a dust molecule, i.e., grains B and C combine to form a dust molecule. Firstly, grains B and C are well separated (Figs. 7 and 8) and their interparticle distance is about 0.2 mm which is larger than Δr_c as indicated by the blue line in Fig. 8(a). The two grains gradually approach each other until their interparticle distance is smaller than the critical value. Then, they form a new dust molecule and their interparticle distance keeps near constant as they travel together as shown in Figs. 7 and 8.

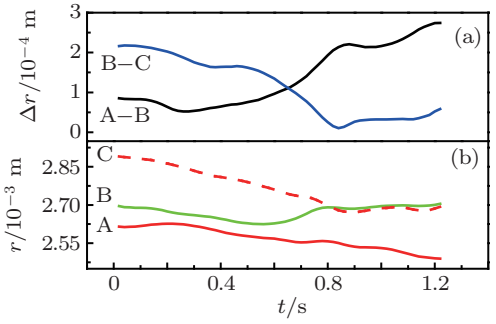


Fig. 8. (color online) Dependences of (a) interparticle distances and (b) positions of dust grains on time. The black (blue) line indicates the interparticle distance of grains A–B (B–C). The green (red) line represents the position of the lower (upper) grain B (A, C).

4. Conclusion

We have studied the formation and dissociation of dust molecules in an rf dusty plasma. The dusty molecule consists of an upper dust grain and a lower one nearby when their interparticle distance is less than a critical value. This critical value in our experiment is about 0.06 mm. The ion cloud in

the wake of the upper dust grain attracts the lower dust grain, which results in the fact that the upper dust grain always leads the lower one as they travel. If the movement of the upper one becomes faster, the lower one would further lag behind the upper one due to the neutral drag. When their interparticle distance is larger than the critical value, the dust molecule would dissociate into two individual grains. Our results are helpful to explore the dynamics of dusty plasma such as the alignment of dust grains.

The ion cloud that originated from the upper dust grain plays an import role in the leading action of the upper dust grain in the dust molecule. If we suppose the lower dust grain leads the upper one, when the lower dust grain moves, it would attract the ion cloud of the upper one, which results in a minute displacement of the ion cloud. However, the effect of ion focus from the upper dust grain will fill this ion void immediately. The ion cloud would "pull" the lower dust grain to its equilibrium position. In other words, the leading action from the lower dust grain is negligible compared with that from the upper one.

From the viewpoint of symmetry, the dipole of dust grain–ion cloud has an asymmetrical structure. This is the reason why the upper dust grain leads the lower one instead of the opposite. Recently, Morfill *et al.* obtained a symmetrical quadrapole of ion cloud–dust grain–ion cloud in microgravity dust plasma by applying an ac voltage.[18] Strings consisting of symmetrical quadrapoles were observed. The interparticle interaction is reciprocal (Hamiltonian). However, if a dc voltage is applied, an asymmetrical dipole of the dust grain–ion cloud is obtained. The interparticle interaction is nonreciprocal (non-Hamiltonian) in this case.[19] The interparticle interaction between the asymmetrical dipole (induced by the dc bias of sheath) and the lower dust grain in our experiment is also nonreciprocal, which gives rise to the leading movement of a dust molecule.

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