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Influence of gas pressure on the pattern evolutions of dust clusters and fractals in a dusty plasma system

Huang Feng(黄 峰)†, Ye Mao-Fu(叶茂福),
Wang Long(王 龙), and Jiang Nan(江 南)

Institute of Physics, Chinese Academy of Sciences, Beijing 100080, *China*

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Dusty plasma has been produced through chemical reaction in a capacitively coupled radio frequency (rf) discharge system. Dust clusters with a few particles and dust fractals are observed. As gas pressure is increased, the suspended height of dust particles descends and the average interparticle distance decreases accordingly. The influence of gas pressure on the pattern evolutions is investigated. Dust clusters or fractals not only can evolve regularly on a horizontal plane, but also can evolve from a horizontal plane to a vertical line array. Under appropriate conditions, the evolutions are reversible. When the evolution is from a symmetrical pattern with a centre particle to another pattern, the centre particle will first show its unsteadiness.

Keywords: dusty plasma, pressure, pattern evolution
PACC: 5225Z, 5240

1. Introduction

Dusty plasma can be defined as ionized gases with dispersed charged solid particles of micron to submicron sizes. Dusty plasma exists widely in astrophysics, such as in planetary rings, interstellar clouds, and comets.[1] In microelectronic industry, dust contamination can cause circuit failure.[2] In addition, dusty plasma can provide a new model system to study dynamics and phase transition in condensed matter physics.[3−5]

Dust particles are often negatively charged due to the higher thermal mobility of electrons than ions. In general, the particles have great charge and low temperature, which cause the strong interaction of particles by screen Coulomb potential. Thus, a dusty plasma system is also called a strong Coulomb coupling system.[6−9] When the Coulomb potential energy of interparticle is sufficiently larger than their thermal energy, Coulomb crystals will be formed by dust particles.[1,10,11] Dust particles are levitated by the plasma sheath force. Particles are inclined to form several layers above the electrodes according to their different masses.[11] The particles are confined by the plasma sheath, which means that appropriate electrode shapes can easily trap particles. If particle size dispersion and charge dispersion are small, then dust particles in every layer can form an ordered array.[11−13]

In our experiment, dust particles grow from small to large through chemical reaction. At the stage of small particles, say dust cloud, individual particles cannot be discerned and the behaviour of the dust cloud is similar to fluid, which will be reported elsewhere. When the particles grow larger and can be discerned, they can form regular lattice patterns or fractals. In space, the particles can form funnel shape, shuttle shape, and dome shape, which are determined by experimental conditions.

Patterns of dust lattices and clusters have been investigated in detail by many groups, who mainly research the static structures of the patterns on certain planes.[6,11−16] In this paper, we mainly focus on the pattern evolutions of dust clusters and fractals from a horizontal plane to a vertical line array as gas pressure changes.

2. Experimental setup

The experimental setup is a capacitively coupled

†E-mail: huangf@aphy.iphy.ac.cn

rf discharge system (13.56MHz). The discharge electrodes are composed of a cylindrical inner electrode (Φ=79mm, h=17mm) with a cone-shaped hole in the centre (Φ=10mm, h=6mm) and a hollow thin-wall cylindrical outer electrode (Φ=96mm). The function of the hole in the inner electrode is to confine particles easily. The mixture gases of silane–ethylene–argon with a fixed partial pressure ratio of 1/4/19 are used to produce dust particles through chemical reaction during discharge. As for the initial discharge parameters, the background pressure is kept less than 5Pa, the filled mixture gases are often at above 100Pa, and the rf power is usually above 10W. After the mixture gases are filled into the discharge chamber, the gas pressure is adjusted only by adjusting pumping speed, instead of additionally filling in mixture gases. Dusty plasma phenomena can be obtained within 1 min after the rf power supply is switched on. After the onset of discharge, the rf power and working gas pressure is adjusted to 2–20W and 10–600Pa, respectively. Fluid-like patterns of small particles, regular lattice patterns of large particles, and fractal patterns can be observed at different stages of particle growth. Dust particles can be easily gathered above the inner electrode through the plasma sheath force and illuminated through laser light scattering (LLS). The laser sheet beam with a thickness of 400 μm is produced by a He–Ne laser (632.8nm), which passes through a lens group and a cylindrical lens. The laser sheet beam can be adjusted up and down to observe the behaviour of dust particles in space. The movements of particles are monitored through a CCD (charge coupled device) camera with a microscope mounted above the discharge chamber and recorded through a computer with a frame grabber software.

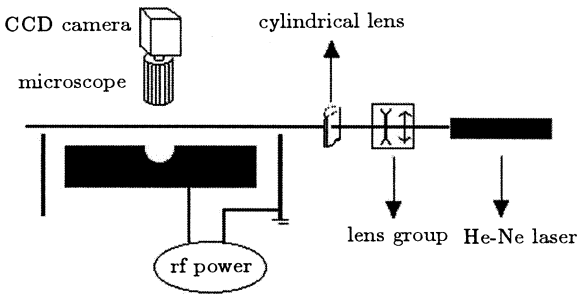


Fig.1. Experimental setup.

3. Phenomena and analyses

A dust cloud composed of many nano-size dust particles can be obtained soon after the onset of discharge. It behaves as a fluid and can form various interesting patterns, which will be discussed elsewhere. In order to obtain larger mass and more stable particles, we keep the rf power and gas pressure higher for a long time to make the small particles grow or coagulate sufficiently, then slowly decrease rf power or increase gas pressure to slow down their movements. After that, a regular lattice pattern formed by a number of particles is easy to be observed. In order to study the pattern evolution formed by a few particles, we should release some particles from the lattice pattern and leave the wanted number of them. By careful adjustment, we can obtain any number of particles we want, which can also self-organize into some regular patterns. For a fixed number of particles, the patterns can evolve on the same horizontal plane: for example, the evolution of rectangle–triangle–pentagon shape of six particles. This phenomenon has been explained in detail.[15] However, such an investigation mainly focuses on the evolution on the same horizontal plane. In our experiment, we also observe the evolution occurring on different planes. Here, we mainly present the pattern evolution of dust clusters and fractals from a horizontal plane to a vertical line array with changing gas pressure.

3.1. Dust cluster patterns evolve on a horizontal plane

Figure 2 shows three examples of cluster patterns with different numbers of particles on one horizontal plane. We can see that the particles can form regular geometric shapes, such as quadrangle, pentagon, and pentagon with a centre particle, which are determined by the number of particles. Such regular patterns are the result of the self-organization of dust particles.

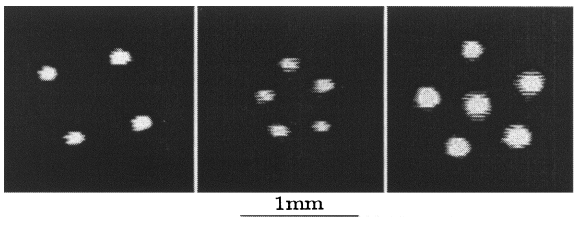


Fig.2. Three patterns with different numbers of particles.

Particles of a fixed number can demonstrate several regular patterns on the same horizontal plane during the change of gas pressure. Figure 3 represents the pattern evolutions of four particles trapped near the hole when the rf power is kept at 12W and the gas pressure is increased from 150 to 220Pa. With

the increase of the gas pressure, the pattern gradually evolves from the rhombus-like shape to the triangle-like shape. This evolution is along the direction of the lowest potential energy.[15] If the four particles are suspended far away from the hole through adjusting gas pressure, we cannot find the triangle shape. We think this phenomenon is due to the strong radial restriction of the sheath force, which has a relation to the cone-shaped hole and will push the particles towards the centre.

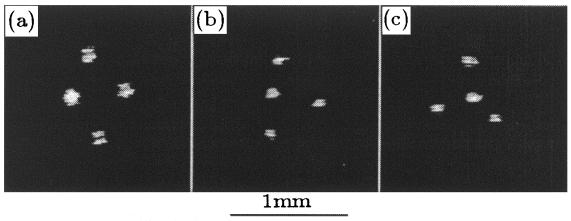


Fig.3. Four-particle patterns change with increasing gas pressure.

Figure 4 shows that the average interparticle distance among these four particles changes with the gas pressure. With the increase of the gas pressure, the average interparticle distance gradually decreases. When the gas pressure is less than 100Pa, the influence of gas pressure on interparticle distance is more apparent than that under higher gas pressure. That is why there is no great change in the average interparticle distance when gas pressure changes from 150 to 220Pa (Fig.3).

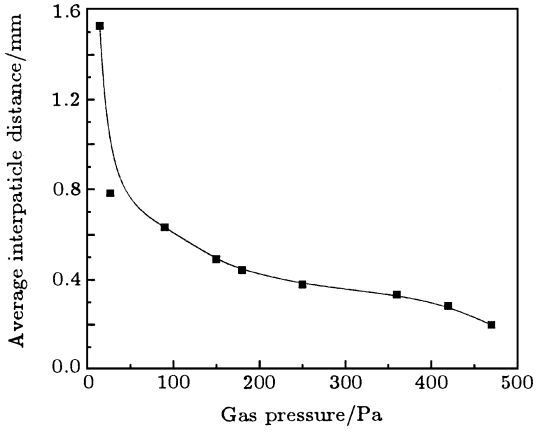


Fig.4. The average interparticle distance among four particles versus gas pressure.

It should be pointed out that changing gas pressure also influences the suspended height of all particles, which is also caused by the sheath force influenced by gas pressure. As is well known, dust particles are suspended by the plasma sheath force. The suspended height of a particle is mainly determined by the competition of two forces in the vertical direction, i.e. the gravity and the vertical component of the sheath force. The balance of these two forces makes the particle stay steadily at a certain height. Decreasing the gas pressure makes the ionization degree increase, and therefore the electric field of plasma sheath increases accordingly. Thus, all the particles will be levitated higher by the plasma sheath force.

The change of the plasma sheath shape is very steep near the hole or in the hole. When the suspended height is far higher than the inner electrode surface, the restriction of the radial component of the sheath force on the particle becomes very weak. Then the Coulomb repulsion force will result in the increase of interparticle distance. Thus, decreasing gas pressure not only raises the suspended height of particles, but also increases the interparticle distance. Contrarily, if the gas pressure is increased gradually, the particles will descend gradually, until they fall into the hole. At the same time, the interparticle distance decreases accordingly. As for the cluster patterns (for example four-particle clusters), there are different patterns between the steeper sheath shape near the hole and the flatter sheath shape far away from the hole. The triangle patterns (Figs.3 (b) and (c)) cannot be observed if the particles are levitated over 4mm above the inner electrode surface.

3.2. Dust cluster patterns evolve from a horizontal plane to a vertical line array

Figure 5 shows a short period during the evolution of seven particles within 9s when the pressure is increased from 35 to 49Pa and the rf power is kept at 2W. These particles are recorded on the same horizontal plane, which is about 2mm above the inner electrode surface. Here the distances between particles have no great change since the change of gas pressure is small. We can see that the particle number on the horizontal plane is decreasing gradually. In fact, when the gas pressure is continuously increased, finally only one particle can be seen on this plane (the figure is not shown here). This situation is also seen in Fig.3. The evolution process will become quicker if the gas pressure is increased more quickly. This phenomenon does not mean that the particles disappear gradually with increasing gas pressure. In fact, these particles arrange themselves into a vertical line array at last, which has been observed through a side-illumination but not recorded here. However, after the formation of a vertical line array of the particles, if the gas pressure

is decreased slowly, then the particles in a vertical line will be turned back to the original horizontal plane. This indicates that the evolution process is reversible if experimental parameters are controlled strictly and steadily. However, if the particles are big enough, they will drop onto the electrode surface during the increase of gas pressure and cannot be levitated again despite the decrease of the gas pressure.

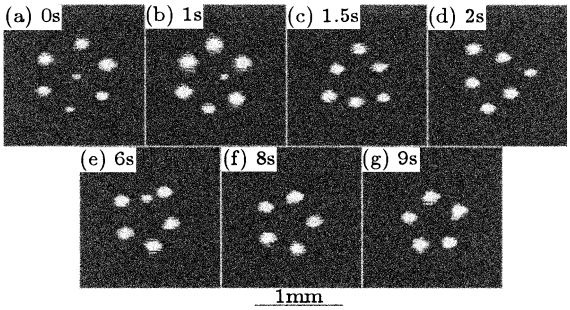


Fig.5. Changes of seven-particle pattern as the gas pressure is increased from 35 to 49Pa.

Figure 6 shows the approximately reversible process of four particles (trapped very near the hole) when the gas pressure is in the range of 250 to 600Pa and the rf power is kept at 12W. Figure 6 (a) shows that when the gas pressure is increased from 250 to 600Pa within 5min, the particles located on a horizontal plane gradually evolve into a vertical line array. Figure 6 (b) shows that all the four particles gradually go back to the original horizontal plane when the gas pressure is decreased from 600 to 250Pa within 3min after the formation of a vertical line array. So, it is a reversible process. However, we can still see the difference between these two reversible processes, that is, the positions of particles. It is due to the rotation phenomena during the pattern evolution process, which have been verified by our observation. It should be pointed out that such rotation phenomena of the particles as a whole or one around another are observed without application of magnetic field (Figs.3, 5, and 6). The rotation is not always in the same direction, for example, it can be clockwise–stable–anticlockwise. Sometimes, clockwise rotation and anticlockwise rotation occur alternately. This rotation is caused by the interaction of particles trapped near the hole, where there is a strong radial restriction making the particle movement difficult in the radial direction, whereas the particles move more easily in the tangential direction. As a result, the rotation phenomena are observed due to the particle interactions in the tangential direction. Here, the different speeds of gas pressure change between the two reversible processes probably influence the particle interaction indirectly.

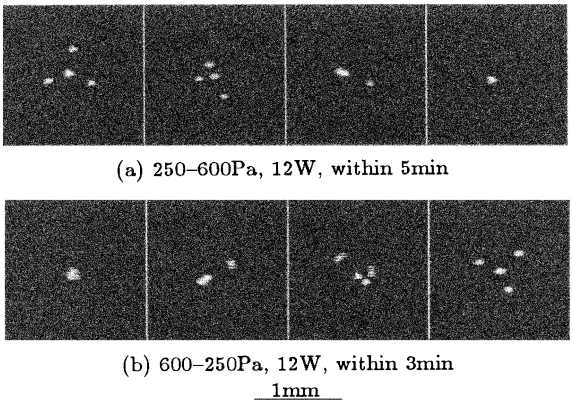


Fig.6. The approximately reversible evolution of four-particle pattern as the gas pressure changes.

In addition, an interesting phenomenon is observed with increasing gas pressure. During the evolution from the symmetrical pattern with a centre particle to another pattern, the centre particle first shows its unsteadiness. Figure 7 shows the example of this situation (see also Figs.5 (a) to (c)). It indicates the change of location of the centre particle when the rf power is kept at 2W and the pressure is increased from 29 to 49Pa. With increasing gas pressure, the centre particle first descends a little (Fig.7 (b)) and then it moves outwards slowly. When the distance between this centre particle and another outer particle reaches a certain value, these two particles suddenly attract each other, and finally the centre particle lies below the other particle. This makes the particle number decrease on the original horizontal plane (Fig.7 (c)). The residual particles on the horizontal plane will continuously evolve until a second particle cannot be seen on that plane. Finally, the particles will form a vertical line array. From Fig.7, we can see the influence of gas pressure on interparticle distance and suspended height again. The decrease of suspended height makes the particles depart a little from the original illumination plane, which makes the centre particle in Fig.7 (b) and the particles in Fig.7 (c) look smaller.

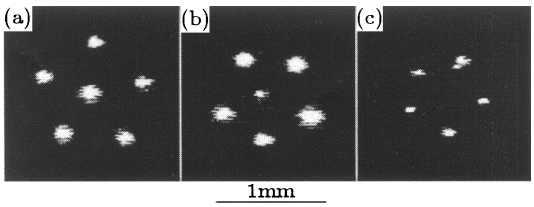


Fig.7. An example of the evolution from the symmetrical pattern with a centre particle to another pattern (29–49Pa, 2W).

Why does the centre particle first show its unsteadiness? The symmetrical pattern with a centre particle is the more steady state for the patterns with a fixed particle number on a horizontal plane.[15] All outer particles are at the same status whether in the vertical direction or in the radial direction (Fig.3 (c) and Fig.7 (a)). As for the centre particle, it is stable in the radial direction. However, a small disturbance will make it unstable in the vertical direction for lack of vertical Coulomb coupled force. Slowly increasing gas pressure makes the suspended height of the centre particle lower and it will depart from the original illumination plane a little, so it looks smaller than before (Figs.5 (a) and 7 (b)). When it descends to a certain plane, which can keep its equilibrium at this height under a certain gas pressure, it can move more freely on that plane for lack of confinement of surrounding particles. Small disturbance in the radial direction will make it move in the radial direction. Finally, it will array under a particle on the original plane, possibly through the attraction force between different layers.[17] But the residual particles on the original plane will continuously evolve as the gas pressure continuously increases, until all the particles arrange in a vertical line. However, even if the evolution is not from the symmetrical pattern with a centre particle to another pattern, the particles still have the trend to form a vertical line array.

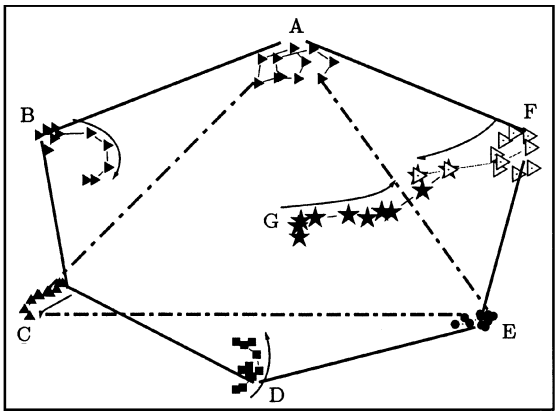


Fig.8. Changes of seven-particle pattern from the hexagon-like shape to the triangle-like shape.

Figure 8 shows in detail the evolution process of the symmetrical seven-particle pattern with a centre particle (corresponding to Figs.5 (a) to (c)), that is, from the hexagon-like shape (solid line) to the triangle-like shape (dashed line) when the gas pressure is increased a few Pa. The most apparent change is that the centre particle G and the particle F move towards each other. The particles A, C, and E have smallest movements and eventually they become the three vertices of the triangle, while the particles B and D move towards the sides of the triangle. In our experiment, dust particles grow through chemical reaction, so the charge and mass of all particles are not the same. However, the particles can still self-organize into such regular patterns.

3.3. Fractal patterns evolve from a horizontal plane to a vertical line array

Similar phenomena of the cluster patterns evolving from a horizontal plane to a vertical line array are also observed in fractals. Figure 9 shows the evolution process of many fractals when the gas pressure is increased from 140 to 150Pa and the rf power is kept at 12W. During this evolution, many fractals arrayed in the vertical direction form a beautiful cone shape in space, which is due to the electrode shape with a cone-shaped hole in the centre. If the gas pressure continuously increases, only one fractal section can be seen on that plane finally (Fig.9 (d)). But it is difficult to operate the opposite evolution process, for the fractals have larger masses and will drop onto the electrode surface with increasing gas pressure and cannot be levitated again. Thus, for fractals, this evolution is not reversible. Some regular geometry shapes are also observed during the evolution (Figs.9 (b) and (c)). However, the fractals show a much more complicated and interesting evolution process than cluster patterns. It should be pointed out that some particle-like shapes in Fig.9 should be the cross-section of fractals on that horizontal plane.

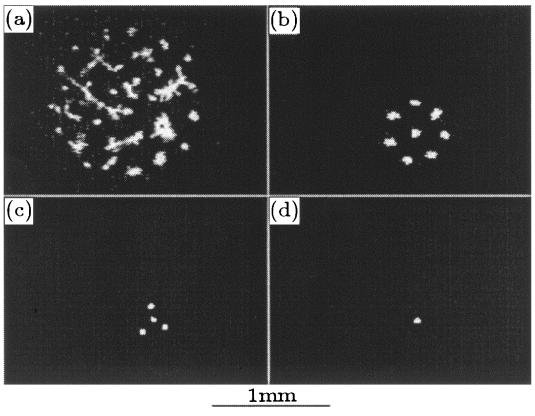


Fig.9. Evolution of fractals as the gas pressure is increased from 140 to 150Pa.

4. Conclusions

In conclusion, the influence of gas pressure on the

evolution of dust cluster and fractal patterns has been investigated. It is shown that changing gas pressure can influence the average interparticle distance and the suspended height of particles. With the increase of gas pressure, dust cluster and fractal patterns will experience the evolution from one horizontal plane to a vertical line array. This evolution can be reversible under appropriate conditions.

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