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Angular Velocity Saturation in Planar Dust Cluster Rotation

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Abstract

Dust clusters, consisted of one up to twelve particles arranged in a horizontal plane, were formed in an inductively coupled rf plasma. When an axial magnetic field was applied to the dust clusters, the clusters rotate collectively in the left-handed direction with respect to the field. It was observed in our cluster rotation that, for single ring cluster, the angular velocity of the rotation increased linearly as the magnetic field strength increased. And for double ring dust clusters, the angular velocity increases linearly at low magnetic field and but then saturated at high magnetic field ($\sim$ 60G). Comparison of our experimental results with theoretical models from literature has been made and an explanation for the angular velocity saturation of the dust cluster rotation has been provided.

Dynamics of dust clusters with different numbers (2 to 12) of micron-sized particles levitated in a horizontal plane is studied experimentally in an inductively coupled magnetised dusty plasma. When the magnetic field was absent, the clusters exhibited small random fluctuation but always remained around their equilibrium position. And when an axial magnetic field with strength up to 90 G was applied normal to the cluster plane, the dust cluster was observed to undergo rotational motion as a rigid body. At such low magnetic field strength, the electrons are fully magnetized, the ions are partially magnetized, and the dusts are unmagnetized. Since the direction of the rotation was in the left-handed direction with respect to the magnetic field, so presumably, the cluster rotation is mainly due to the collisional drag from the azimuthal component of the ion flow. S. Shimizu *et al.* [1] and Konopka *et al.* [2] have performed similar experiments and have provided theoretical models based on ion drag and fluid equations to explain how such rotation arises. Their experimental results were verified and it agrees well with their model. However, in our experiment, we were able to rotate the dust clusters by utilising a magnetic field of only tens of Gauss, which was 2 to 3 order less than that used in previous experiments and predicted by theory. In particular, when the angular velocity of the cluster rotation was analysed, its dependency on the magnetic field strength varies for clusters with different number of particles and structural configuration. This differs from the result reported by the other experimental groups.

In this article, we offer an alternative interpretation of the experimental results by comparison with the different models. Moreover, we give an alternative explanation of the angular velocity saturation observed in cluster rotation. The study of our results is important because there are many situations in astronomy, laboratory and material fabrication industry where we have strongly coupled dusty plasmas in magnetic fields. A better understanding of the underlying physics will provide various applications across a range of field.

The experiment is conducted in a radio-frequency (rf) discharge with a printed-circuit board (PCB) electrode system. The detailed configuration of the apparatus was described in earlier papers [3–5]. Figure 1 shows the interior of the experimental apparatus. Argon gas at a pressure of 100 m torr is used for the discharge. A 500 mV peak-to-peak RF voltage at 17.5 MHz is provided from the signal generator onto the RF coil to form the plasma. The plasma density, electron temperature has been measured to be $\sim 10^{15}\,\mathrm{m}^{-3}$ and ~ 3 eV, respectively. The ion temperature is assumed to be at room temperature ~ 0.026 eV. The dust particles used to form the cluster are mono-dispersed melamine formaldehyde polymer sphere with diameter of $6.21 \pm 0.09\,\mu\mathrm{m}$, density of $1.51\,\mathrm{g\,cm}^{-3}$, and typical charge of $\sim 10^4\,e$. The dust cluster formed above the confining electrode are illuminated by a fully height adjustable He–Ne laser. The motion of the dust crystals was observed under the microscope and from the video images generated from the cameras. The images of the rotational motion were then recorded on videotapes at a frame rate of 50 fps and a shutter speed of 0.008 s. The particles are then tracked with a software program that outputs the x and the y-coordinates of their trajectories as a function of time for analysis.

Dust clusters of different number of particles were formed and levitated in a horizontal plane above the magnetic coil. Figure 2 shows the angular velocity dependence on magnetic field strength for the different clusters. In general, the angular velocity of the cluster rotation increases as the magnetic field strength increases. Single ring clusters (planar-2, -3 and -4) require certain threshold magnetic field strength before rotation will initiate. The threshold magnetic field strength decreases as the number of particles in the cluster decreases. And when rotation is initiated, the angular velocity increases linearly as the magnetic field increases. "One and a half" ring clusters (planar-6, -7 and -8), which are single ring clusters with one dust particle at the centre, are much easier to rotate. Their angular velocity also increases linearly as the magnetic field strength increases. Interestingly, the angular velocity of double ring clusters only increases linearly for lower fields but then saturates at higher values.

It should be mentioned that, in contrast with experiments in dc discharge and capacitive rf-discharge, we needed only relatively small magnetic field ($\sim$ 30 G) to rotate the dust clusters and observe the angular saturation effect.

We attribute the angular velocity saturation to the decrease in driving force at the inner ring of double ring dust clusters. Since the moment of inertia of the double

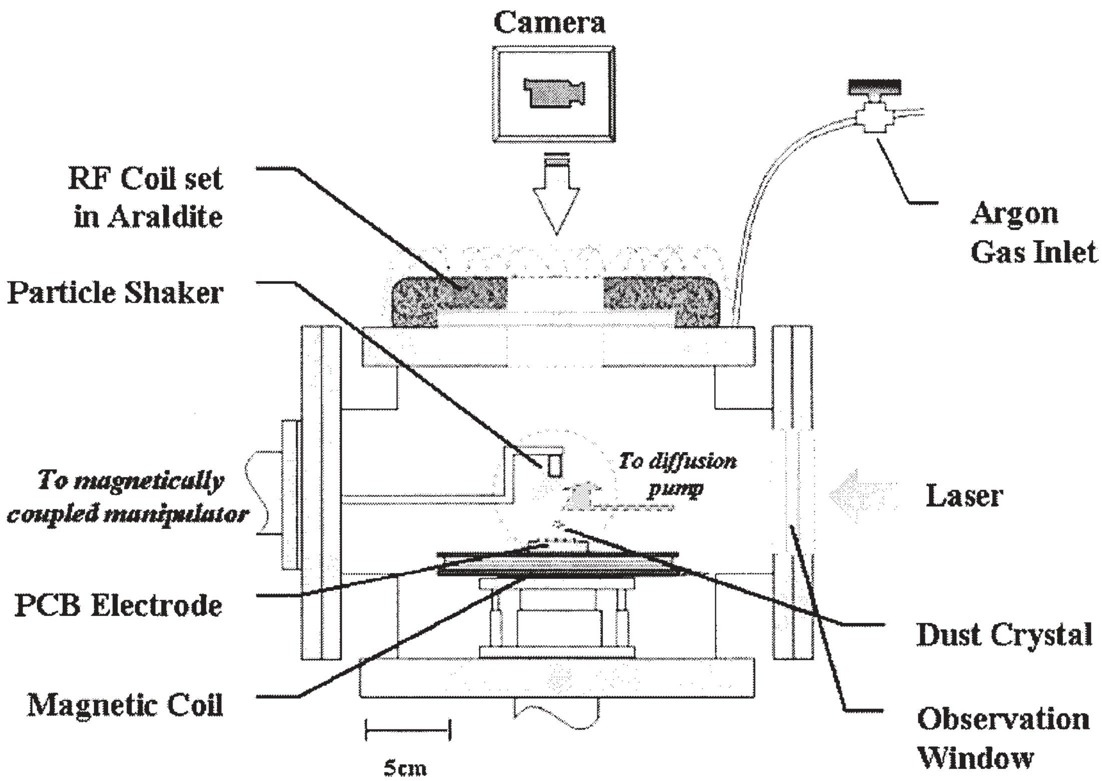

Fig. 1. Experimental apparatus used in the cluster rotation experiment.

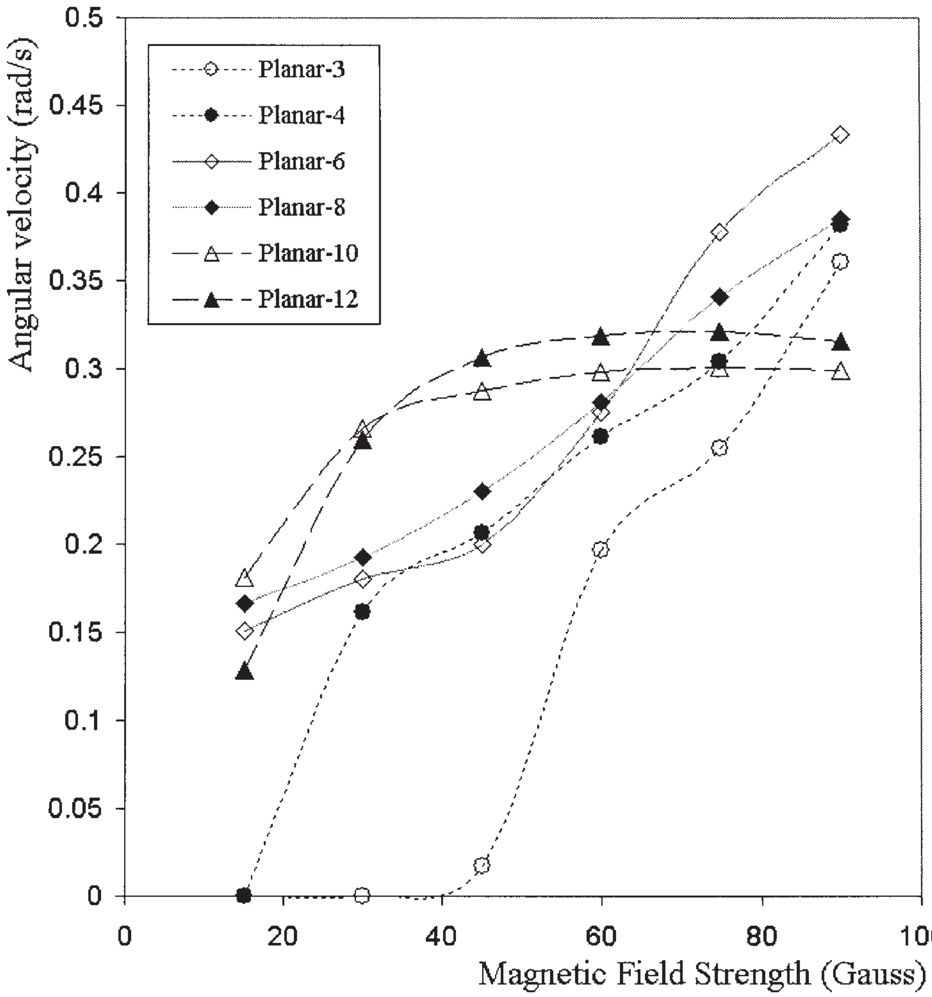

Fig. 2. Angular velocity dependence on magnetic field strength for different cluster configuration.

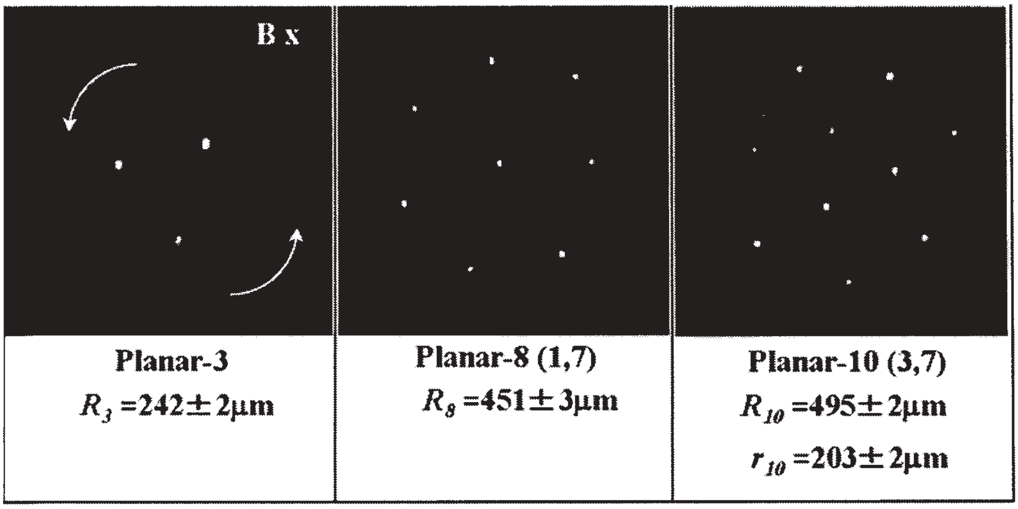

Fig. 3. Captured images, structural configuration, outer radius and inner radius of planar-3, planar-7 and planar-10.

ring cluster does not change in rotation and the cluster remains as a rigid body due to the strong Coulomb interaction between the particles, if there is a decrease in the driving force on the inner ring of the cluster, the net result will be a decrease in the angular velocity.

The analysis of single ring planar-8 cluster and double ring planar-10 cluster can be used as an example to demonstrate our model (see Fig. 3). Planar-8 has seven particles on the outer ring with mean diameter $\sim 450\,\mu$m and one particle at the centre. Now from the equation of neutral drag, the friction of each dust particle is given by

$$F_{ND} = \kappa\omega_8 R_8 \quad (1)$$

where κ is a constant $\sim 3.43 \times 10^{-12}$ sN m^{-1}, ω is the angular velocity of the cluster rotation, R is the outer radius of the cluster. And from the equation of azimuthal ion drag, the driving force on each particle is given by

$$F_{ID} = \alpha B_8 + \gamma \quad (2)$$

where α and γ are constants. And B is the magnetic field strength. Here we made the assumption that the radial electric field E_r does not change when magnetic field changes. We will show later that this is in fact not the case and magnetic field does modify the radial electric field in our system. This is evident by the decrease in size in the dust cluster as we increase the magnetic field (see Ref. [3]). But since $E_r \sim B^n$, so $F_{ID} \sim E_r B \sim B^{n+1} \sim B$ for small $n \sim 0.5$–1. So for approximation purpose, our model will still be accurate. Assuming that the ion drag is the driving mechanism for the cluster rotation, and then we can equate Eqs. (1) and (2) and obtain the values of α and γ from planar-8 to be $\sim 3 \times 10^{-14}$ NT^{-1} and $\sim 2 \times 10^{-16}$ N, respectively.

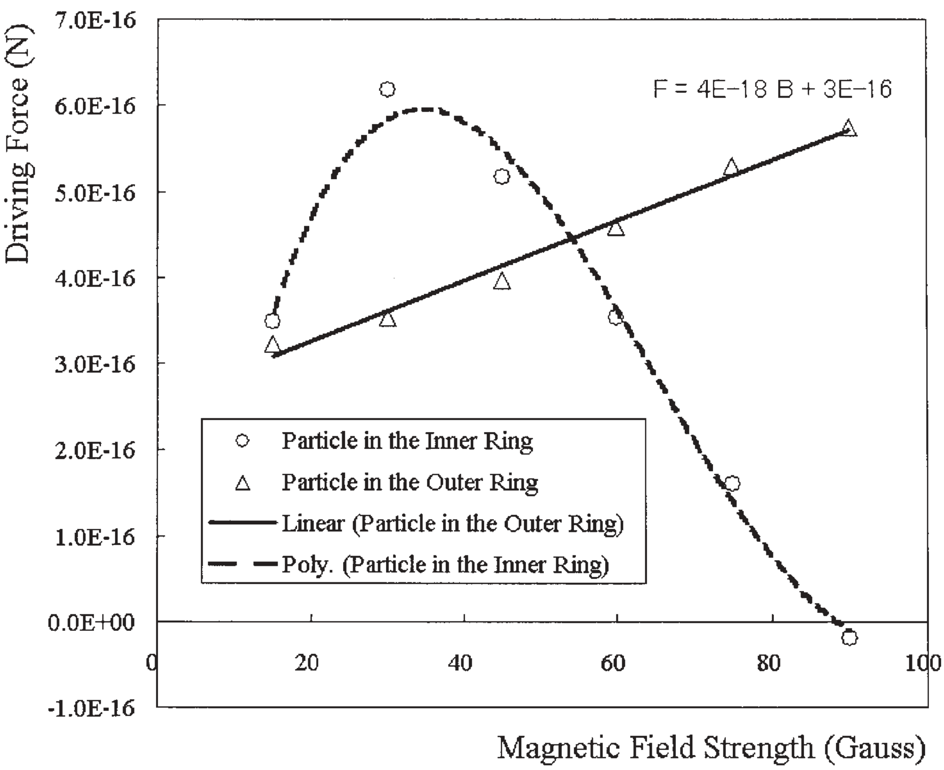

Fig. 4. Comparison of the calculated value of the driving force acting on the inner ring and the outer ring for planar-10 as magnetic field increases.

Now planar-10 structural configuration consists of seven particles on the outer ring with mean diameter $\sim 500\,\mu m$ and 3 particles on the inner ring with mean diameter $\sim 200\,\mu m$. We assumed that the same nature of ion drag force, which acted on the outer ring of planar-8, acts on the outer ring of planar-10. In addition, there will be a driving force F_I^D acting on the inner ring of planar-10. So the equation of motion is given by

$$7\xi(\alpha B_{10} + \gamma) + 3F_I^D = 7\kappa\omega_{10}R_{10} + 3\kappa\omega_{10}r_{10} \tag{3}$$

where $\xi = R_{10}/R_8$ is the scaling factor and r is the inner radius of the cluster. And hence the driving force acting on per particle in the inner ring is given by

$$F_I^D = \kappa\omega_{10}\left(\frac{7}{3}R_{10} + r_{10}\right) - \frac{7}{3}\xi(\alpha B_{10} + \gamma). \tag{4}$$

We can substitute the experimental values from planar-10 into the equation and obtain the values of driving force on the dust particles in the inner ring as a function of magnetic field. Figure 4 shows the driving force on the particles in the outer ring and inner ring of planar-10 as a function of magnetic field. As we can see, the driving force acting on the inner ring increases initially at low field values and then gradually decrease at high field values. It should be mentioned that since the diameter of planar-3 is 25% larger than the inner ring of planar-10, the nature of this driving force did not violate the linear dependency we observed for planar-3.

From the experiment, dependence of radial electric field on magnetic field was observed [5]. Our data show that $E_r \sim B^{0.5}$ or B. Since electric field is modified by the magnetic field, it should be taken into account in the analysis of the driving force of cluster rotation. But for our model, it is appropriate to make the approximation as in Eq. (2).

The Larmor radius for electrons and ions are 6×10^{-5} m and 2×10^{-2} m, respectively. So the electrons are highly magnetized compared to the ions. And because the ratio of electron gyrofrequency to electron–neutral collisional frequency is about 1.5 (for ions, this ratio ~ 0.01), the electrons will tend to be localized at the centre of the system. As a result, the non-uniform distribution of the charge density will lead to a change in the electric potential profile. In fact, this phenomenon can explain the saturation in angular velocity for double-ring clusters. As the magnetic field increases, the radial electric field at the centre of the cluster will eventually decrease and might even change into the opposite direction. Consequently, the driving force acting on the particles in the inner ring of the cluster will decrease. However, due to the strong inter-particle force, the cluster remains as a rigid body, and so the net torque on the whole cluster will decrease. Thus saturation of double-ring cluster rotation occurs.

Our model would be consistent with the results from Sato *et al.* [1,6] because a larger confinement potential was used in their experiment. Hence, a larger magnetic field would be necessary for them to observe the saturation effect. It should be stressed that, unlike in Sato's experiment, the ion–neutral collisional mean free path ($\sim 4 \times 10^{-4}$ m) in our system is of comparable size to our dust cluster. So the collisional fluid description of the ions might not be appropriate in this case. Our experimental results will be interesting as the ions are in the nonlocal collisionless fluid stage.

In conclusion, it was observed that for a single ring cluster, the angular velocity of the rotation increases linearly as the magnetic field strength increases. And for double ring dust clusters, the angular velocity increases linearly at low magnetic field but then saturates at high magnetic field ($\sim$60G). We attribute this saturation to the change in the driving force on the inner ring of the cluster as the magnetic field increases.

Acknowledgments

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