Experimental investigation on lane formation in complex plasmas under microgravity conditions

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Abstract. A series of experiments dedicated to probing the phenomenon of lane formation in binary complex plasmas over a broad range of parameters has been performed with the PK-3 Plus laboratory on board the International Space Station (ISS) under microgravity conditions. In the experiments, bunches of small particles were driven through a background of big particles. We show that the dynamics of lane formation varies considerably with the density of the background and the size ratio between small and big particles. For consecutive injections of small particles a memory effect of the previous penetration was discovered for the first time. This memory effect was investigated quantitatively with respect to the structure formation and the penetration speed. We show that the memory effect in lane formation is linear. In addition, we studied the crossover from lane formation to phase separation driven by the nonadditive interactions between small and big particles. We found that during this transition the small penetrating particles effectively cage the background particles. Online supplementary data available from stacks.iop.org/NJP/14/073058/mmedia

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1. Introduction

Pattern formation in complex fluids has been a long-standing, intriguing topic, e.g., electric-field-induced pattern formation in colloidal dispersions [1], and ‘oscillons’ self-organized into clusters in granular materials [2]. The dissipative interactions through friction are a source of nonlinear dynamics and complexity which result in pattern formation on large scales. A complex plasma showing non-Newtonian behavior [3] and visco-elasticity [4] as a complex fluid is also the host of various pattern formation phenomena, e.g., plasma crystals [5–7], coaxial ring patterns in strong magnetic fields [8] and lane formation [9]. Lane formation is an evolving pattern formation that occurs when two species of particles are driven into each other. Like-driven particles form lanes and move collectively. Typically, the lanes exhibit considerable anisotropic structural order accompanied by an enhancement of mobility. Lane formation was discovered in complex plasmas in 2009 [9] and has been studied both experimentally [10] and numerically [11].

A complex plasma is comprised of ions, electrons, neutral gas and immersed particles, whose diameters range from the nanometer scale to several hundreds of micrometers [12, 13]. Those particles are charged either positively or negatively depending on the dominant charging mechanism [14, 15]. For low-temperature laboratory gas discharges, particles of micrometer size (microparticles) acquire negative charge due to the higher mobility of electrons, where the net charge is roughly proportional to their size. The resulting surface potential is screened by ions and electrons inside the plasma, which leads to repulsive Yukawa-type interactions. Under microgravity conditions the microparticles are trapped in the plasma potential well, and tend to form a homogeneous three-dimensional (3D) cloud usually with a void in the center [16]. Within the cloud, particles experience not only Yukawa-type interaction but also an electric force due to the plasma potential well, friction due to the neutral gas and an ion drag force due to the ion flow.

In this paper, we review a series of experiments on the lane formation observed in complex plasmas under microgravity conditions. The experiments presented here were performed in the PK-3 Plus laboratory [17] on board the International Space Station (ISS). The paper covers all lane formation experiment data from July 2006 until January 2011. This paper is organized as follows. In section 2, we introduce the setup of the PK-3 Plus laboratory, describe the experiment procedure and mention their limits. In section 3, the analysis method for quantifying
the lane structure is described in detail. In sections 4–7, we investigate different aspects of lane formation. Finally, the conclusions are presented in section 8.

2. The experimental setup and procedures

PK-3 Plus is the second-generation microgravity laboratory that was specially designed for complex plasma research on board the ISS [17]. Different types of experiments have been performed including externally excited wave propagation [18], heartbeat oscillation [19], plasma crystal formation [20], etc. The setup consists of a capacitively coupled radio-frequency (rf) chamber and surrounding infrastructure including laser illumination, a gas system, a video recording system, a vacuum system, as well as a control system. The chamber itself has a cubic shape and contains two circular electrodes that are 3 cm from each other, as shown in figure 1(b). Each electrode has a diameter of 6 cm and is surrounded by a grounded guard ring of 1.5 cm width. Each guard ring includes three dispensers, which allow the injection of monodisperse microparticles of six different sizes: silica microparticles with a diameter of $1.55 \pm 0.04 \mu m$ and melamine-formaldehyde (MF) microparticles with diameters of $2.55 \pm 0.04$, $3.43 \pm 0.06$, $6.81 \pm 0.1$, $9.19 \pm 0.09$ and $14.9 \pm 0.26 \mu m$. The particles can be injected by shaking the dispenser controlled by a coil. The injected particle number can be tuned by varying the shaking time. The glass walls are made of quartz through which the dynamics of individual particles and the structure of the microparticle cloud can be recorded by three CCD cameras: the ‘overview (OV) camera’ includes the whole area inside the chamber, the ‘high resolution (HR) camera’ focuses on the center of the chamber and a ‘glow camera’ (not shown in the figure) records the plasma discharge with a similar field of view as the OV camera. In our experiments on lane formation, the videos are all recorded by the ‘quadrant view (QV) camera’, which records only half of the field of view captured by the OV camera with a higher spatial resolution. The maximal recording speed for all four cameras is 50 fps (frames per second). As shown in figure 1, the particles are illuminated by a laser sheet with a full-width at half-maximum (FWHM) of about $80 \mu m$ at the focal axis perpendicular to the cameras’ line of sight. The cameras and lasers are mounted on a translation stage which can move back and forth with a given speed. This function makes it possible to scan the particle cloud in the chamber and obtain 3D information. However, due to the limited scan speed, it is not possible to visualize the 3D information in some experiments with fast dynamics, such as lane formation.

The experiment procedure is relatively simple. After igniting the argon plasma, we inserted a relatively large number of particles of one type to fill the chamber and waited for a while to let the particles form a homogeneous background cloud. Then we injected particles of another species which are smaller than the existing particles in the chamber. We distinguish between the two particle species based on their kinetics. The small particles penetrate into the cloud of big particles due to the driving force $F_d$ resulting from the electric force (plasma potential), ion drag force and neutral friction. Whether the lane structure can be formed during the penetration depends on several factors including the number density ratio, the size ratio between big and small particles and plasma parameters such as plasma potential. While the small particles penetrate the background cloud, the nonadditivity between small and big particles (an asymmetry in the mutual interactions between particles of different species [21]) leads to phase separation. The small particles start to form a dense droplet that finally settles around the central void.

The plasma conditions cannot be controlled directly. They depend on several control parameters such as the neutral gas type, neutral gas pressure, discharge power and the number of
Figure 1. A sketch of the PK-3 Plus plasma chamber (b) and the particle observation system, with the definition of the coordinate system used throughout the paper. Panel (a) shows the top view of the chamber. The laser and the recording system are mounted on a translation stage that can move back and forth in the z-direction. The laser light is focused into a vertical sheet, approximately 80 µm wide in the focal plane. A total of six particle dispensers can independently inject mono-disperse spherical microparticles into the chamber. Panel (b) shows the side view of the chamber, along the cross section through the center.

microparticles injected into the discharge. In all the cases studied, lane structures of background particles are formed, unless the input power is too low to sustain a stable particle cloud [19].

The experiments described in this paper are performed in argon gas at a pressure of 30 Pa and at a peak-to-peak rf voltage of 40 V. This results in an effective current $I_{\text{eff}} = 6 \text{ mA}$ measured on the electrodes. Some experimental measurements of the plasma parameters in the PK-3 Plus chamber in ground-based conditions have recently been reported [22]. In order to get the order of magnitude estimate for the present experimental conditions, we use the results of SIGLO-2D plasma simulation published earlier [17]. For the above-mentioned conditions, the plasma density at the center of the discharge chamber (in the absence of particles) is estimated as $n_e \simeq n_i \simeq n_0 \simeq 8 \times 10^8 \text{ cm}^{-3}$ and the electron temperature is $T_e \simeq 4 \text{ eV}$. The ion temperature is expected to be equal to the neutral gas temperature $T_i \simeq T_n \simeq 0.025 \text{ eV}$. This results in the ion (electron) Debye radius of $\lambda_{Di} \simeq 40 \mu \text{m}$ ($\lambda_{De} \simeq 500 \mu \text{m}$) and the ion mean free path of $l_i = 70 \mu \text{m}$. The particle charges are then estimated taking into account the collisional [23] and ionization-enhanced [24] ion collection by the particle. The resulting charges are summarized in table 1. We point out that the presence of particles in the discharge can modify plasma parameters. In particular, the ion density in the particle cloud should exceed the electron density to keep quasi-neutrality. This, in turn, lowers the particle charges in comparison with the individual particle regime. We expect, however, that these effects are not dominant under the conditions investigated, since the value of the Havnes parameter $P = (a T_e / e^2)(n_p / n_0)$ remains below unity in all the experiments discussed in this paper [25] (here $a$ is the particle radius and $n_p$ is the particle number density).

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Table 1. Values of the (individual) microparticle charge $Q$ estimated for the conditions relevant to the described experiment (see the text).

| $2a$ (µm) | 2.55 | 3.4 | 6.8 | 9.2 | 14.9 |
|-----------|------|-----|-----|-----|------|
| $|Q/e|$     | 1400 | 1900| 4500| 6900| 14300|

The particle number density ratio can be tuned relatively precisely and the size ratio between big and small particles is defined within a few per cent. Due to the mounting location of dispensers on the chamber and the camera position, only dispensers 2 and 3 (cf see figure 1), which contain MF particles with diameters of 2.55 ± 0.04 and 3.43 ± 0.06 µm, can be used for the penetration experiments. Particles injected from dispenser 3 enter the field of view from the left and their motion towards the center can be fully resolved: we call this ‘in-plane injection’. In contrast, particles injected from dispenser 2 move in the line of sight of the camera. Thus, they move perpendicular to the field of view, which allows us to record a full cross section through the penetration region, but not the motion of individual small particles: this is denoted as ‘in-the-line-of-sight injection’. Dispenser 1 injects 1.55 µm particles from the right-hand side. This field of view is visible only with the OV camera, the resolution of which is too low to identify the particle positions and motion.

3. The analysis method

In this paper, we focus on the lane structure formed by big particles in the background during the penetration. In order to quantify such structures, we employ the anisotropic scaling index method (ASIM) to realize a local nonlinear measure for structure characterization [26]. The ASIM has been applied to various studies, for instance complex plasma [27], cosmology [26] and medical image processing [28]. This method detects the ‘local lane structure’ of each particle by assessing the local scaling properties of particle density in the neighborhood. The size of the neighborhood and the degree of anisotropy are controlled by two additional characteristic parameters: the length $R$ and aspect the ratio $\epsilon$ of ‘ideal’ lanes.

For a given set of particle positions, $\{r_j\}$, $j = 1, \ldots, N$, the anisotropic scaling index $\alpha$ is defined as

$$
\alpha(r_j, R, \epsilon, \theta) = \frac{2 \sum_{k=1}^{N} (d_{jk}/R)^2 e^{-d_{jk}/R^2}}{\sum_{k=1}^{N} e^{-d_{jk}/R^2}},
$$

where $d_{jk} = d(r_j, r_k, \epsilon, \theta)$ is the distance between particles $j$ and $k$ in a space stretched by $\epsilon$ along the direction $\mathbf{u} = (\cos \theta \sin \theta, -\pi/2 \leq \theta \leq \pi/2)$. In practice, we transform the coordinates of particle positions in the new space by applying a stretch matrix $\Lambda = \begin{pmatrix} 1 & 0 \\ 0 & \epsilon \end{pmatrix}$ and rotation matrix $\Omega = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$ on the experiment coordinates, i.e. $r_j' = \Lambda \Omega r_j$, and thus, $d_{jk} = |r_j' - r_k'|$. By determining the value of $\theta$ that maximizes the difference $\alpha(r_j, R, \epsilon, \theta + \pi/2) - \alpha(r_j, R, \epsilon, \theta)$, we obtain a ‘preferred’ direction $\mathbf{u}_j$ associated with particle $j$, signifying the local anisotropy. The ‘length’ of this anisotropy is given by $R$ and $\epsilon$ describes the ratio between its ‘length’ and ‘width’.

In order to characterize the global laning of big particles in each single frame, we define a laning-order parameter $S_0$, which is the largest eigenvalue of a second-rank tensor $T = 2N^{-1} \sum_{j=1}^{N} \mathbf{u}_j \otimes \mathbf{u}_j - I$, where $I$ is an identity matrix. $S_0 = 1$ denotes perfect alignment.
(of the preferred angles), while $S_b = 0$ represents a perfectly random phase. Because of the similar morphology of the lane structure in the experiments presented in this paper, we use the same spatial scale $R = 1200 \mu\text{m}$ and the anisotropic aspect ratio $\epsilon = 5$ throughout this analysis. The value of $R$ corresponds to the typical length of lanes in our experiments and the value of $\epsilon$ represents the typical length to width ratio.

4. Dependence of lane formation on the number density ratio

The number density ratio between the background and the penetrating particles is one of the most important factors influencing lane formation in our experiments. We study three cases with low, medium and high density clouds of small particles (MF particles with a diameter of $3.4 \mu\text{m}$) injected into the same background cloud of large particles, one after another. The background particle cloud (MF particles with a diameter of $6.8 \mu\text{m}$) is prepared prior to the start of injections and is not replaced between injections. As some volume around the central void is occupied by small particles, the initial number density of the background is increased slightly after each injection. In order to inject small particle clouds with different densities, we set the shaking time ($t_s$) of the particle dispenser to three different values: (I) low $t_s = 31 \text{ ms}$, (II) medium $t_s = 33 \text{ ms}$ and (III) high $t_s = 35 \text{ ms}$. Generally speaking, the longer the shaking time, the more particles are injected. As this increases the number of particles injected as one bunch, this effectively results in denser small particle clouds (see also the next paragraph).

To estimate the number density ratio $n_s/n_b$, where $n_s/n_b$ is the number density of small/big particles, we select a fixed square area in the center of the penetration region, as shown in figure 3, where we count the number of small (big) particles $N_s$ ($N_b$): $n_s/n_b = N_s/N_b$. When the small particles pass through the penetration region, $N_s$ increases, while big particles are expelled and $N_b$ decreases. Please note that the variation of $N_b$ with time is the same during penetration for all three injections. The change of $n_s/n_b$ results from the change of $N_s$, i.e. from the increased density of the small particle cloud. The number density ratio $n_s/n_b$ for all three cases is shown in figure 2.

We quantify the lane structure formed by big particles during penetration by ASIM described in the previous section. For the purpose of eliminating boundary effects and to define the penetration region, we select an ROI (see figure 3). The same ROI is used for all three injection cases. Figure 3 summarizes the results for the three injection cases. For every case it shows two diagrams. In the left column the morphology for in-plane injection is visualized: all positions of small (in red) as well as big (in cyan) particles from 250 frames ($\simeq 5 \text{ s}$) are superimposed into a single picture. When the small particles are injected from the dispenser mounted on the top flange, the direction of penetration of the small particle cloud is slanted. Apparently, small particles in the upper half of the picture are denser than in the lower half. In this picture a small central square indicates where $n_s/n_b$ was estimated, and the ROI for the calculation of $S_b$ is emphasized. In the right column the temporal evolution of $S_b$ as well as of the particle number in the ROI are shown.

The number of particles in the ROI develops similarly for all three cases. As small particles enter the ROI, big particles are repelled out of the ROI by the small particles. This is possible because the confinement by the plasma potential is weak. As the number density of the small particles is higher than the background cloud, the total number of particles in the ROI is increased during the penetration. As we can see in figure 3, the maximum total number of particles in the ROI occurs at the same time ($t \approx 2 \text{ s}$) for all injection cases. Also the minimum of
Figure 2. Evolution of the particle number density ratio. The number of large ($N_b$) and small ($N_s$) particles is measured in a square close to the center of the penetration region. The number density ratio is given by $n_s/n_b = N_s/N_b$. Three different curves are drawn for three different dispenser shaking times, corresponding to three densities of the injected small particle cloud: (I) $t_s = 31$ ms, low density as red circles, (II) $t_s = 33$ ms, medium density as orange crosses and (III) $t_s = 35$ ms, high density as green triangles.

the number of big particles occurs at the same time ($t \approx 2.5$ s). This implies that the penetration dynamics of small particles is comparable in all three cases.

In contrast, the lane order parameter $S_b$ evolves differently in all three injection cases. It is clearly visible that the lane structure of big particles is only formed in that part of the penetration region where the density of the small particle cloud is high enough, and for the high-density case (III) the order parameter even seems to attain some plateau during the penetration. For case (III) due to the high density of small particles injected, once they penetrate into the big particles, they effectively cage the big particles (as described in detail in section 7). Therefore, the lane structure of big particles is formed instantaneously and maintained until the small particles leave the ROI. In case (I) and also (II), the number density of small particles is not sufficient to cage the big particles everywhere, so that the big particles on the sides can escape across the wings of the small particle cloud. Also note that with increasing density of the small particle cloud, $S_b$ reaches its maximum value earlier: for the low-density case (I) $t_{(I)} \approx 3$ s, for the medium-density case (II) $t_{(II)} \approx 2.5$ s and for the high-density case (III) $t_{(III)} \approx 1.3$ s. This is because at later times even cases (I) and (II) attain sufficient densities inside the ROI to cage the big particles from escaping. Interestingly enough, case (I) reaches the highest value $S_{b(I)} \approx 0.3$, whereas $S_{b(II)} \approx 0.28$ and $S_{b(III)} \approx 0.23$. Even though fewer big particles get caged in case (I), the lanes formed by the big particles have a narrower distribution of preferred angles, which directly leads to a higher value of $S_b$. For case (II) and increasingly so for case (III), the penetration geometry allows for a wider range of preferred angles, and therefore for a systematic decrease of the peak value of $S_b$. Take note that these results are not conclusive, since the evolution of $S_b$ strongly depends on the initial configuration. According to the numerical study presented in [11], $S_b$ varies dramatically for statistically independent but thermodynamically equivalent initial configurations. A huge number of repetitions of the experiment (several hundreds of times according to the simulation) is necessary to obtain a statistically significant lane order parameter. This is not really
Figure 3. Influence of the number density ratio on the dynamics of lane formation. For three different densities of the injected small particle cloud, (I), (II) and (III) from top to bottom (see also movies 1, 2 and 3, respectively, available from stacks.iop.org/NJP/14/073058/mmedia), two pictures are shown. On the left is a superposition of particle trajectories during the penetration (250 frames $\approx 5$ s). The big MF particles (6.8 $\mu$m diameter) are represented in cyan, and the penetrating MF particles (3.4 $\mu$m diameter) in red. The small solid rectangle at the center of the penetration region is used during the estimation of the number density ratio. The dashed line indicates the region of interest (ROI) used during the calculation of $S_b$. On the right, the evolution of the laning order parameter for big particles $S_b$ (crosses), as well as the number of big particles $N_{b,ROI}$ (dashed line) and the total number of particles $N_{s,ROI} + N_{b,ROI}$ (solid line) in the ROI, is shown.
Figure 4. Influence of the size ratio on the dynamics of lane formation (see also movie 4, available from stacks.iop.org/NJP/14/073058/mmedia). On the left is a superposition of particle trajectories during the penetration (250 frames ≃ 5 s). The big background MF particles (9.2 µm diameter) are represented in cyan, and the small penetrating MF particles (3.4 µm diameter) in red. The dashed line indicates the region of interest (ROI) used during the calculation of $S_b$. On the right the evolution of the laning-order parameter for big particles $S_b$ (crosses) as well as the number of big particles $N_{b,ROI}$ (dashed line) and the total number of particles $N_{s,ROI} + N_{b,ROI}$ (solid line) in the ROI is shown.

feasible in our experiments due to the limited resources (gas, particles, operator time) on board the ISS.

5. Dependence of lane formation on the size ratio

In order to compare the influence of the particle size ratio, we use MF particles with a diameter of 9.2 µm as background particles and keep MF particles with a diameter of 3.4 µm as the penetrating particles. The same pressure, rf voltage and ROI as in section 4 are used. As we see in figure 4, the number of big particles and the total number of particles in the ROI are comparable with case (I) of the previous section. However, the maximum of the total particle number and the minimum of the number of big particles occur earlier than for case (I). This implies a higher penetration speed. Also a higher peak value of $S_b$ is attained.

For a combination of particles with larger difference in size, in other words, larger nonadditivity [21], this seems counter-intuitive. The simulation results in [11] show that with higher nonadditivity, particles penetrate slower and the peak value of the laning-order parameter becomes smaller. However, in reality, the situation is more complicated. The change of the size of background particles changes not only the nonadditivity, but also the particle cloud profile as well as the local plasma parameters. The difference between the ion and the electron density tends to be larger in the plasma with bigger particles because of electron depletion due to the higher charge on the surface of big particles [25]. This results in a stronger electric field and therefore increases the driving force and penetration speed. Besides, the coupling strength for the cloud of bigger particles is higher, resulting in a more ordered system. Small particles can
Figure 5. Memory effect on the laning-order parameter. The temporal evolution of $S_b$ is displayed for three sets of two consecutive injections with different intervals $\Delta t$. Symbols with error bars in black, red, and green correspond to the cases with $\Delta t = 3, 5, 12$ s (see also movies 5, 6 and 7, available from stacks.iop.org/NJP/14/073058/mmedia), respectively. The locations of the peaks of $S_b$ are shaded in grey.

penetrate more easily in such a system than in a disordered system. Since the nonadditivity has a minor influence on the lane formation compared to other factors such as particle interaction or driving force, we can conclude from the experiment that a combination of particles with a larger size difference leads to more pronounced lane formation.

6. Memory effect

As mentioned before, when the small particles penetrate the big particle cloud, they repel these background particles outwards, creating sponge-like tunnels. After the small particles have passed through the cloud of big particles, it takes some time for the big particles to relax and refill the empty tunnels [29, 30]. If small particles are injected into the big particle cloud before complete relaxation of the background, the remnant of the sponge-like structure will influence the penetration of small particles and therefore the dynamics of lane formation. We call this the 'memory effect' of lane formation.

In this section, we investigate this phenomenon by injecting two consecutive bunches of small particles with a variable time interval $\Delta t$ in between. We used $\Delta t = 3$ s, $\Delta t = 5$ s and $\Delta t = 12$ s. The memory effect is evaluated in terms of the laning-order parameter of the big particles $S_b$ and the penetration speed of the small particles. The penetrating particles have a diameter of 3.4 $\mu$m and the background particles have a diameter of 9.2 $\mu$m.

Figure 5 shows the temporal evolution of $S_b$. Three messages can be read from the diagram, namely the time separation of peaks by consecutive injections, the relaxation process of $S_b$ and the peak value of $S_b$. For all three cases the laning-order parameter has a first maximum at $t \approx 1.5$ s after the small particles appear in the camera view. The initial value of $S_b$, its rise time, peak value and relaxation for the first injection are basically identical in all three cases. The second peak of the order parameter, however, appears at different times completely determined by the selected injection interval. Of all three cases only for the largest injection time interval $\Delta t = 12$ s is the relaxation time long enough for the laning-order parameter to reach its initial value $S_b \approx 0.08$. That means that the lane structure among the big particles vanishes, and the
The memory effect can also be investigated from the point of view of the kinetics of the small particles. The tunnels left in the background particles during the initial penetration influence the penetration speed of the small particles in the consecutive injection. We investigate this effect by measuring the cumulative difference of mean Gauss-fit penetration speed (x-component of velocity) of small particles between consecutive and initial injection: \( \int_{t_0}^{T} \Delta \bar{v}(t) \, dt \), where \( \Delta \bar{v}(t) = \bar{v}(t + \Delta t) - \bar{v}(t) \), \( \bar{v}(t) \) is the average speed of small particles in the x-direction, \( T \) is the penetration time (integral from \( t_0 = 0.6 \) s in our case), and \( \Delta t \in [3 \text{ s}, 5 \text{ s}, 12 \text{ s}] \) is the selected time interval. The results for all three cases are shown in figure 6. In the case of \( \Delta t = 12 \text{ s} \), the difference varies around zero during the whole penetration process, leading to a cumulative difference slightly above zero. The small particle speed in the consecutive penetration is marginally increased over the initial penetration. Due to the short penetration time and lack of statistics it is not clear if this marginal increase derives from statistical fluctuations or
Figure 7. Illustration of the memory effect on the penetration path taken by small particles. The pictures show a superposition of particle positions of four consecutive frames at three times during the penetration for the time interval $\Delta t = 3$ s. The left picture (a) shows the initial injection, and the right picture (b) the corresponding consecutive injection. Each picture is made up of three panels. Each panel shows a part of the original picture at its original position. The left panel is cut from the original at the time point of 0.7 s after the injection is issued, the central panel at the time point of 1.4 s, and the right panel at the time point of 2.1 s.

from a change in the background structure. For the cases with short relaxation time $\Delta t = 3$ s, 5 s, the penetration speed difference is mainly positive during the penetration. This can be clearly seen as a positive slope of the cumulative difference, indicating a speedup of the consecutive penetration process over the initial one. The dogleg bend of both curves at $t = 1.6$ s happens when the particle bunch from the consecutive injection hits the cloud of small particles from the initial injection close to the center of the chamber. The speedup is mainly caused by the tunnels formed during the first penetration, which dramatically reduces the resistance the small particles experience during the penetration. With the presence of these tunnels, the small particles will mainly follow them, taking the same path as in the previous penetration, as can be seen in figure 7. With the longer time interval $\Delta t = 12$ s, small particles take completely different paths to penetrate the background particle cloud.

7. Crossover from lane formation to phase separation

As we described in the previous sections, each experiment goes through three main stages. Initially, the small particles are injected into the plasma and move under the influence of the inhomogeneous plasma potential. Then they enter the background cloud of big particles where lane formation can occur. Finally, when the small particles approach the center where the driving force exerted on small particles, $F_d$, decreases due to the effective potential configuration, phase separation of small and big particles due to nonadditivity starts to dominate and the small particles form a droplet. Between all three stages there is a smooth transition. The transition from the injection to the laning stage is significantly influenced by the initial configuration of the contact, which has been extensively studied numerically in [11]. During the laning stage the small and big particles form an array of interpenetrating lanes [9]. At the final stage of the
The cage effect. Small MF particles (a) with diameter $3.4 \, \mu m$ are injected in-plane and (b, c) with diameter $2.5 \, \mu m$ are injected in-the-line-of-sight into a background of big particles with diameters $6.8$ and $14.9 \, \mu m$, respectively. The pictures are a superposition of particle positions for (a) 250 frames and (b, c) 200 frames, with penetrating small particles in red, and background big particles in cyan. Picture (a) is adopted and magnified from picture (b) in figure 3. The in-the-line-of-sight pictures have been recorded with a shifted $z$-position of the laser and camera system, (b) $z = 24 \, mm$ (see also movie 8, available from stacks.iop.org/NJP/14/073058/mmedia), and (c) $z = 19 \, mm$ (see also movie 9). The two vertical gray bars at $x = -24 \, mm$ and $x = -19 \, mm$ in (a) indicate the equivalent positions of the laser planes used for pictures (b) and (c).

experiments, the ratio of the magnitude of the driving force to the nonadditivity parameter, $R = F_d / \Delta$, describes the competition between lane formation and demixing, similar to the Weber number in a macroscopic fluid system, which is used to determine the transition from lane formation to the classical Rayleigh–Taylor instability [31]. As the ratio $R$ decreases the penetrating particles form a separated droplet (composed of small particles only) that moves as an ensemble towards the center of the chamber. This phenomenon is generally known as demixing (phase separation) [11, 21, 32].

During the crossover from the laning stage to the phase separation stage there is a change in the laning mode, from free lane formation to a demixing dominated mode, where the interior part of the small particle cloud already forms a honeycomb-like substructure, in which big particles can be effectively caged, while big particles closer to the wings of the small particle cloud are quickly expelled (see section 4 and figure 8). During this crossover, lanes are formed by the big particles only. To finally form a dense cluster of small particles (see figure 9), the lanes of big particles are expelled from the rear of the honeycomb structure. This is an important process in the phase separation dynamics.

The cage effect and the crossover can be better visualized in the in-the-line-of-sight injection. Due to the limitations of the setup configuration (camera position and dispenser arrangement) as described in section 2, we are not able to perform experiments with the
Figure 9. Crossover from lane formation to phase separation. Small MF particles (a) with diameter 3.4 µm are injected in-plane and (b) with diameter 2.5 µm are injected in-the-line-of-sight into a background of big particles with diameters 6.8 and 14.9 µm, respectively. The pictures are a superposition of particle positions for (a) 250 frames and (b) 200 frames, with penetrating small particles in red, and background big particles in cyan. Picture (a) is an extension of picture (a) in figure 8. The in-the-line-of-sight picture has been recorded with a shifted $z$-position $z = 14$ mm of the laser and camera system (see also movie 10, available from stacks.iop.org/NJP/14/073058/mmedia). The vertical gray bar at $x = -14$ mm in picture (a) indicates the equivalent position of the laser plane.

same particle combinations as for in-plane injection. Therefore, we used MF particles with a diameter of 2.5 µm as the penetrating particles and MF particles with a diameter of 14.9 µm as background particles. This makes it easier to distinguish particles of different types in the recorded movies. Here, we do not intend to make quantitative comparison but only demonstrate the cage effect qualitatively.

As we can see in figures 8(b) and (c), the small particles form a honeycomb structure, penetrating the big particle cloud. These pictures show two cross sections through the system 24 and 19 mm away from the center of the chamber in the $z$-direction. The equivalent positions of these layers in an in-plane injection are indicated as gray bars in figure 8(a), which is adopted and magnified from figure 3(b). The honeycomb structure is visible as a band structure in the in-plane injection. Within the cells of such a honeycomb structure, big particles are caged and form lanes. The big particles in the perimeter of the small particle cloud move outwards when the small particles contact and penetrate the respective layers. This corresponds to the repulsion of big particles from the ROI mentioned in the previous section. These particles move back to their original positions after the small particles leave the layer, resulting in curly trajectories.

When we look at the cross section closer to the center of the chamber ($z = 19$ mm), the small particle cloud becomes much denser, so that the cells of the honeycomb structure shrink dramatically. The system starts the crossover from lane formation to phase separation.
The fully phase separated particle cloud in the vicinity of the void \((z = 14 \text{ mm})\) is shown in figure 9. The big particles are almost completely expelled out of the small particle cluster so that the honeycomb structure of small particles vanishes. At this moment, small particles and big particles demix completely and phase separation of the two particle species is achieved.

8. Conclusion

To conclude, we have presented a series of experiments on lane formation under microgravity conditions on board the ISS with the PK-3 Plus setup. Big particles form pronounced lane structures when small particles are driven and penetrate through them. A sensitive lane-order parameter based on anisotropic scaling indices enabled us to identify an optimal number density ratio between small and big particles for the lane formation. It is also found that big particles are more easily caged between the lanes formed by small particles if the number of injected small particles is increased. These caged big particles form streaming lanes and result in a peak value in the lane-order parameter. As the small particles leave the big particle cloud, the leftover cavities in the big particle cloud are refilled with big particles due to relaxation. By tuning the time interval between two consecutive penetration events of small particles, we investigated the ‘memory’ effect of the previous penetration on the consecutive one. The shorter the time interval, the greater the number of tunnels left from the initial penetration and the faster the small particles penetrate through the background particle cloud. We found that the peak values of the lane-order parameter from all cases with different time intervals are all about 0.22, which indicates that the ordering of the laning pattern has no evident dependence on the time interval and that the memory effect is linear. These leftover cavities from the previous penetration event serve as fast channels for the consecutive injection event and result in a clear speedup of the penetration of small particles. In addition, a crossover from free lane formation to a demixing dominated mode of the nonequilibrium system has been observed.

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