Density waves at the interface of a binary complex plasma

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Abstract – Density waves were studied in a phase-separated binary complex plasma under microgravity conditions. For the big particles, waves were self-excited by the two-stream instability, while for small particles, they were excited by heartbeat instability with the presence of reversed propagating pulses of a different frequency. By studying the dynamics of wave crests at the interface, we recognize a "collision zone" and a "merger zone" before and after the interface, respectively. The results provide a generic picture of wave-wave interaction at the interface between two “mediums”.

Wave behavior at the interface consists of various interesting phenomena including transmission, reflection and refraction, etc. [1] The early study of refractions can be dated back to the year 984, when Snell’s law was first proposed by a scientist, Ibn Sahl, in Baghdad [2]. Up-to-date studies of waves at an interface include not only light waves [3], but also acoustic waves in solids [4] and fluids [5], capillary waves in liquids [6], electromagnetic waves [7], charge density waves [8], and spin waves [9]. These studies result in wide applications such as dental diagnostics [10] and study of seismic waves in geoscience [11]. Recent progresses in granular matter [12] and colloidal physics [13] enable us to study the wave behavior at an interface with resolution of individual particles. However, rigid contacts in dense granular matters and strong dissipation in solvent in colloids prohibit studies at the kinetic level.

Dust density waves in complex plasmas provide a unique opportunity to study various aspects of wave propagation. A complex plasma is a weekly ionized gas containing electrons, ions, neutral atoms and small macroscopic particles [14,15]. Such a system allows experimental studies of various physical processes occurring in liquids and solids at the kinetic level [16]. Since the first observation of self-excited dust acoustic waves, dust density waves have drawn much attention [17–20]. Streaming ions generate a Buneman-type instability [21]. Thus, dust density waves can be self-excited if internal sources of free energy exist [18]. They can also be triggered by the heartbeat instability [22,23]. The particle dynamics can be recorded by video microscopy [24]. While some properties of waves such as growth and clustering can be studied by recording the dynamics of wave crests alone [25–28], tracking individual particles in waves reveals the wave-particle dynamics in much detail [24,29,30]. Apart from self-excited waves, external excitation can also sustain continuous waves [31,32] or trigger solitary waves in complex plasmas [33,34].

A complex plasma consisting of two differently sized microparticles is known as binary complex plasma. Under certain conditions, two types of particles can be mixed and form a glassy system [35]. Other phenomena such as phase separation [36,37] and lane formation [38] can also be studied in such systems. Recently it was discovered that phase separation can still occur due to the imbalance of forces under microgravity conditions despite the criteria of spinodal decomposition not being fulfilled [39]. An interface between two different types of particles emerges in such binary systems.
Despite plenty of studies on dust acoustic waves in past years, it is not clear how two waves of different origins interact at an interface. In this letter, we study the density waves at the interface of a phase-separated binary complex plasma under microgravity conditions. The emergence of two frequencies due to different excitation origins and the respective features in terms of kinetics of individual particles are reported. A detailed study of the periodogram reveals characteristic zones in the vicinity of the interface where waves in two “mediums” strongly interact.

The experiments were performed in the PK-3 Plus laboratory on board the International Space Station (ISS). Technical details of the setup can be found in [31,40]. An argon plasma was produced by a capacitively coupled radio-frequency (rf) generator in push-pull mode at 13.56 Hz. We prepared a binary complex plasma by sequentially injecting melamine formaldehyde (MF) microparticles of two different sizes in the plasma discharge. The mass density of the microparticles is \( \rho = 1.51 \text{ g/cm}^3 \). The small particles have a diameter \( d_s = 6.8 \mu \text{m} \), while the big ones have a diameter \( d_b = 9.2 \mu \text{m} \). With video microscopy [40], a cross-section of the left half of the particle cloud (illuminated by a laser sheet) was recorded with a frame rate of 50 frames-per-second (fps) and a spatial resolution of 0.05 mm/pixel.

As we see in fig. 1(a), initially at a pressure of 20 Pa, microparticles formed a 3-dimensional (3D) cloud with a particle-free region in the center (void) [41,42]. Two particle species were phase-separated with a clear interface (highlighted by a grey curve) due to the following two mechanisms: First, the disparity of particle size \((\Delta d/d \approx 0.3)\) was larger than the critical value of spinodal decomposition (0.25) [36]. Second, both particle species were subjected to two forces under microgravity conditions, namely ion drag force (directed outwards) \(^1\) and the electric-field force (directed inwards). The total force acting on two particle species had a subtle difference depending on the particle diameter [39]. The synergistic effect of spinodal decomposition and force difference led to the instantaneous phase separation. Particularly the second effect drove the small particles into the inner part of the particle cloud and left big particles outside, as shown in fig. 1(a).

The waves were excited as the neutral gas pressure was lowered below a critical value (15 Pa) [24]. As we see in fig. 1(b), at the pressure of 10 Pa the particle cloud was compressed vertically by the expansion of the sheath, and the waves propagated through the entire cloud from the right to the left. The wave crests had a convex shape due to the configuration of the 3D particle cloud. In this letter, we focus on the waves in the region of interest (ROI) with a vertical width of 2 mm (marked by a blue square in fig. 1(b)) around the middle plane where the wavefront can be approximated as flat plane. The average number

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\(^1\)The ions flow outwards from the cloud center (marked by a cross in fig. 1) on average, namely from the right to the left in fig. 1 [40].
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Table 1: Parameters including average number density \( \langle n \rangle \), charge \( Q \) and speed of sound \( C \) estimated for small and big particles. Among these parameters, the charge and the speed of sound are estimated based on three theoretic models: The drift motion limited theory (DML) [44], the modified orbital motion limited theory (mOML) [45] and the orbital motion limited theory (OML) [46].

| \( d \) (\( \mu \text{m} \)) | \( \langle n \rangle \) (mm\(^{-3} \)) | \( Q_{\text{DML}} \) (10\(^{4}e \)) | \( Q_{\text{mOML}} \) (10\(^{4}e \)) | \( Q_{\text{OML}} \) (10\(^{4}e \)) | \( C_{\text{DML}} \) (mm/s) | \( C_{\text{mOML}} \) (mm/s) | \( C_{\text{OML}} \) (mm/s) |
|---|---|---|---|---|---|---|---|
| 6.8 | 240 | 1.0 | 0.9 | 1.4 | 10.5 | 9.5 | 12.9 |
| 9.2 | 60 | 1.7 | 1.4 | 1.9 | 7.0 | 5.9 | 7.6 |

As we can see in fig. 1(b), the interface smeared out as the waves developed. However, the position of the interface can still be extrapolated during the process of pressure decrease. Obviously, the wavelength \( \lambda \) is not constant over the entire dust cloud. The right part has a larger wavelength than the left part. This is clear in the periodogram in fig. 2(a) (see also the video supplemental\_1.avi in the supplemental material). The plot takes 500 consecutive images registered from the experiment. Each vertical column was obtained by averaging over the vertical axis of the ROI in one frame (see the area enclosed by the blue rectangle in fig. 1(b)) [24]. Clearly the periodogram is divided into left and right parts, corresponding to the big and small particles. By linearly fitting the wave crests (bright pixel clusters) for the two parts separately, we obtain histograms of the wavelength and period from the spatial and temporal distances of the wave crests respectively, shown in fig. 2(e), (f). We determine the mean values of the data by fitting a robust Gaussian to the smoothed histogram. For the waves propagating in the small particles, we have wavelength \( \lambda_b = 4.2 \pm 0.3 \text{ mm} \), wave period \( T_b = 0.28 \pm 0.01 \text{ s} \), frequency \( f_b = 3.6 \pm 0.1 \text{ Hz} \), and phase velocity \( v_b = 14.2 \pm 1.0 \text{ mm/s} \). For big particles, we have \( \lambda_b = 1.8 \pm 0.3 \text{ mm}, T_b = 0.19 \pm 0.02 \text{ s}, f_b = 5.4 \pm 0.5 \text{ Hz}, \) and \( v_b = 9.9 \pm 1.8 \text{ mm/s} \).

The fluctuation spectrum of the binary complex plasma is shown in fig. 3. The discrete spectrum suggests the presence of heartbeat oscillation harmonics, while the waves in the continuum are identified as the dust acoustic waves\(^2\) [48].

The characteristic frequencies of the self-excited waves can also be obtained by directly applying fast Fourier transformation (FFT) on the image intensity evolution of the periodogram (representing the number density). The results are shown in fig. 2(c). For big particles \((x < 10 \text{ mm})\), we see one characteristic frequency of 5.4 Hz, in agreement with the analysis of the periodogram. At the interface \((x \approx 13 \text{ mm})\), the peak at 5.4 Hz is suppressed while another characteristic peak at 3.6 Hz starts to emerge. The latter corresponds to the eigenfrequency of small particles. Inside the sub-cloud of small particles \((x > 16 \text{ mm})\), one sees both peaks at 3.6 Hz and 5.4 Hz. For the edge of the void, both the fundamental frequency at 1.8 Hz and its harmonics are visible.

To further study the dynamics of individual particles in the waves, we plot the kinetic periodogram in fig. 4(a), in which the intensity is logarithmically proportional to the mean square speed of the most mobile particle fraction (fastest 25\%). Because of the limited frame rate of the cameras in the PK-3 Plus laboratory on board the ISS, particle velocity cannot be derived directly from particle tracking for such fast moving and dense particle clouds. However, we can still estimate the particle speed by dividing the length of the elongated shape of individual particles (see the inset in fig. 1) by the exposure time of each image. Considering the frequencies of waves of small and big particles, we select the least common multiple of the periods \((\approx 0.6 \text{ s})\) as the duration to perform an averaging process over 3s for better visualization\(^3\). For big particles,

\(^2\)Note that fig. 3 shows the spectrum with both positive and negative wave numbers. In principle the waves can propagate in both directions [47].

\(^3\)The time span covers two periods for small particles and three periods for big particles.
the kinetic periodgram exhibits a leftwards propagating feature with a frequency of 5.4 Hz, corresponding to the result of FFT analysis. However, for small particles we see a cross-shaped trellis. The leftwards propagating wave has a frequency of 3.6 Hz, while the rightwards propagating pulses have a frequency of 5.4 Hz, which is already exhibited in the FFT map in fig. 2(c). The maximal particle speed in the rightwards propagating pulses can reach \( \sim 35 \pm 5 \text{ mm/s} \) while that in the leftwards propagating waves is \( \sim 27 \pm 4 \text{ mm/s} \).

Several effects contribute to the origin of the waves: There is a heartbeat vibration visible in the electric signals (1.1 Hz, see fig. 2(b), (d)). The particle movement in the cloud at this frequency is shifted by friction (\( \approx 10 \text{ s}^{-1} \)), so that only harmonics of 1.8 Hz are excited as waves in the particle cloud. In the small particle sub-cloud close to the void, the waves excited at approximately 3.6 Hz also show reversed propagating pulses with a frequency of 5.4 Hz. The latter pulses correspond to the contracting phase of the heartbeat and this suggests that this wave was excited by the heartbeat instability. In the big particle sub-cloud, the waves did not transmit through the interface (suppression of the 5.4 Hz peak at the interface, shown in fig. 2(c)). This suggests that the wave was self-excited by the two-stream instability. However, the heartbeat (generally affecting the entire dust cloud [22,23]) may synchronize the frequency to its third harmonics.

We measured the particle number density \( n_c \) and absolute speed \( |v_{x,c}| \) at wave crests (ignoring those at wave troughs) and plot them along the \( x \)-axis in fig. 4(b), (c).

This number density is relatively low close to the void and the edge\(^4\). As we can see in the figure, \( n_c \) is lower in big particles than in small particles. The drop starts at \( x \approx 16 \text{ mm} \) and reaches a stable level at \( x \approx 13 \text{ mm} \), where the interface is roughly located (marked by the red dashed line). We highlight this drop by the orange solid line. For the absolute speed of particles, we see a distinct valley at the interface, where the left shoulder starts at \( x \approx 10 \text{ mm} \) (blue dash-dotted line) and the right shoulder starts at \( x \approx 16 \text{ mm} \) (black dash-dotted line).

To better understand the subtle change of frequency and wavelength, we zoom into the area close to the interface marked by a yellow square in fig. 2(a) and show the details in fig. 5(a). At \( x \approx 16 \text{ mm} \) the wave crests start to bend and we can see the emergence of a new wavefront between two existing wave crests at \( x \approx 13 \text{ mm} \). We highlight five typical wave crest pairs by different colors in fig. 5. The transmitting wave crests from small particles to big particles appear as solid curves, while the self-excited wave crests starting at the interface appear as dashed curves. Due to the “collision” of the wave crests (with high concentration of heavily charged particles), the phase speed \( |\nu| \) decreases for the transmitting waves. Accordingly, \( |\nu| \) for the self-excited waves increases, as clearly demonstrated in fig. 5(b). As both waves propagate towards the cloud edge, they can either merge to one wave crest (orange-red

\^4\text{For small particles the number density } n_c \text{ at wave crests is comparable with the average value. However, for big particles } n_c \text{ is much greater. This indicates that particle concentration is much lower in the wave troughs in big particles than in small particles.}
and cyan-green) or coexist and propagate further (green-yellow). This explains the transition of the frequency of 3.6 Hz in small particles to 5.6 Hz in big particles.

To gain better statistics, we tracked all the wave crests close to the interface in fig. 2, calculated the phase speed and show the results with errors (1σ deviation) in fig. 5(c). The drop of the phase speed of the transmitting wave is still clearly visible while the collision of the waves crests snears out due to the randomness of the merge. Combining with the analysis on $n_c$ and $v_{x,c}$, we are able to define the region 13 mm $< x < 16$ mm as “collision zone” and the region 10 mm $< x < 13$ mm as “merger zone”.

In summary, we have presented the first experimental realization of wave propagation across an interface in complex plasmas. The experiments were performed in a binary complex plasma under microgravity conditions on board the ISS. The small particles and big particles were phase separated with an interface in between due to spinodal decomposition and the difference of electric force and ion drag force. For the big particles, waves were self-excited by the two-stream instability, while for small particles, they were excited by heartbeat instability with the presence of reversed propagating pulses of a different frequency. By studying the dynamics of wave crests at the interface, we recognize a “collision zone” and a “merger zone” before and after the interface, respectively. The presented results provide a generic picture of wave-wave interaction at the interface between two “mediums” and may be exceptionally important for particle-resolved studies of interfacial wave phenomena in the future.

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