Nonlinear waves externally excited in a complex plasma under microgravity conditions

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Abstract. An experimental study of intense induced oscillations and nonlinear waves in a complex plasma is presented. The neon plasma is created in the PK-3 Plus set-up on board the International Space Station (ISS) by using a capacitively coupled radio frequency (RF) discharge at a low gas pressure of 16 Pa. The excitation conditions are controlled by a function generator creating a periodic variable modulation at the RF electrodes. In the experiments, comparatively large melamine–formaldehyde particles of 9.2 $\mu$m diameter are used to reduce the damping rate coefficient. The elliptic-shaped particle cloud (with a small central void) of size $65 \times 14$ mm$^2$ was stretched horizontally (parallel to the electrodes) and compressed vertically. Without excitation a weak 5 Hz global breathing mode and weak horizontal waves (approximately with the same frequency) are observed. Increasing the modulation frequency widens the spectrum. The modulation first excites a global vertical slashing mode (at the modulation frequency). At a frequency of 3 Hz intense shaking induces periodic nonlinear wave-ridges in the bottom and top parts of the cloud. The ridges travel at an approximately constant speed of 4–5 mm s$^{-1}$. The modulation also intensifies horizontal waves localized at the horizontal cloud edges, though the regions of intensive waves are visibly disconnected. At higher frequencies the intense wave

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activity involves all the cloud, and ‘oblique’ (quasi-sound) wave-ridges start to propagate through the cloud. Distributions of wave velocity and force fields are analysed.

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1. Introduction

Complex plasmas [1] are low temperature plasmas in which microparticles are embedded as an additional component to ions, electrons and neutral atoms. In a plasma, these micro- (or ‘dust’) particles acquire large negative charges due to the higher electron mobility.

In ground-based experiments, evidently, particles levitate in a discharge chamber if gravity is somehow compensated. Since microparticles are charged, in discharges the natural counteracting agent to gravity is a strong (and favourably directed) electric field which can originate, e.g. in the sheath of radio frequency (RF) discharges [1], or in striations of dc discharges [2, 3], or within a firerod of a Q-machine [4]. Hence the particles are dominantly accumulated by the electric field. Usually pre-electrode discharge electric fields are strongly inhomogeneous. This results in inhomogeneous (highly compressed) complex plasmas.

It is therefore desirable to compensate gravity by another counteracting agent distributed homogeneously, e.g. by thermophoresis [5, 6]. In spite of evident advantages (for instance, the form and position of the particle cloud can be easily externally controlled by applying a suitably chosen temperature gradient), normally the cloud has a complicated ‘sandwich-like’ structure [6, 7].

Performing experiments under microgravity conditions is the only possible way to extend the particle cloud more homogeneously and to fill in practically the entire volume of the discharge chamber [8, 9]. Having a vast particle cloud is an important feature in many experimental aspects of complex plasmas, in particular, for wave excitations.
Table 1. Velocities of the waves observed under different conditions.

| Reference | Gas | Pressure | Particles | $f_{\text{mod}}$ | $v_{\text{ph}}$ |
|-----------|-----|----------|-----------|-----------------|----------------|
| [10]      | N   | 13 Pa    | $\sim 1 \mu m$ Kaolin | 0, 6–30 Hz | 120 mm s$^{-1}$ |
| [21]      | Ar  | 24 Pa    | 3.4, 6.8 $\mu m$ MF | 0–16 Hz | 8 mm s$^{-1}$ |
| [14]      | Ar  | 15 Pa    | 6.8 $\mu m$ MF | — | 16–17 mm s$^{-1}$ |
| [22]      | Ar  | 12 Pa    | 3.4 $\mu m$ MF | 0–35 Hz | 17–25 mm s$^{-1}$ |
| [24]      | Ar  | 25 Pa    | 1.28 $\mu m$ MF | — | 56 mm s$^{-1}$ |
| [25]      | Ar  | 13–26 Pa | $\sim 1 \mu m$ Kaolin | 0, 15–150 Hz | $\sim 100$ mm s$^{-1}$ |

Particles suspended in a plasma can modify the dispersion relations of plasma modes (see, e.g. [10]), but can also give rise to a great many new low frequency wave phenomena such as dust acoustic waves (DAWs) [11] and dust density waves (DDWs) [12, 13]. It is usually believed that DDWs resemble DAWs [14], but for more complicated conditions (and, hence, more applicable to the experiments) they are like highly collisional plasmas with drifting ions.

Predicted first in [11], linear DAWs (with an infinitesimally small amplitude) have been studied theoretically in a number of publications [4], [14]–[17] (for a review, see e.g. [18]). From a theoretical point of view, the DAW is an attractive object because of its quite simple physics: the plasma ions can be treated as inertialless, their contribution is to control the magnitude of electric fields driving the vibrating microparticles. Idealized nonlinear theoretical models have been considered for collisionless soliton-like DAWs, e.g. in [19], and for nondispersive DAW shocks, e.g. in [20]. To the best of our knowledge, nonlinear theoretical models, adequately describing DDWs, have not yet been developed.

From the observational point of view, wave experiments in a complex plasma have an important advantage: particle migrations and rearrangements are easy to follow by illuminating them with laser light and recording the scattered light with a CCD camera. This allows us to observe particle motion in real time at the atomic (kinetic) level.

DAWs have been investigated experimentally, among others, in RF discharges (see e.g. [21, 22] (microgravity conditions), [14] (parabolic flight experiment)), in dc discharges (see, e.g. [16, 23]), and in Q-machines [4, 10].

In [21, 22] waves were excited externally. In [10], the waves were self-excited at sufficiently high discharge currents. The waves were travelling approximately at a constant speed (see table 1 for experimental conditions). In all these cases the waves were suggested to be of linear DAW nature, which was substantiated by adjusting unknown parameters to suit theoretical predictions [11]. For example, the measured wave parameters could be successfully used to estimate the charge of the particles [21, 22, 25].

Piel et al [14] observed oblique self-excited DDWs during a parabolic flight. It was claimed that observations correspond well to the theory proposed in [26], though the dynamics of the particle motion inside the waves was not analysed.

The instability threshold and the detailed dynamics of self-excited DDWs were investigated at the kinetic level in [24]. The observed nonlinear density perturbations were travelling at a speed of $56 \pm 4$ mm s$^{-1}$, the measured particle charge was 2300e. The high registration rate (1000 fps compared to 100 fps in [14]) allowed a number of particle tracks to be traced, and, hence, the structure of wave ridges to be studied in detail. A simple model based on the particle flux balance was proposed which agreed well with observations.

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Thomas et al [25] studied the behaviour of DAWs in a dc discharge at modulation frequencies higher than 100 Hz. They found a linear superposition of self-excited and driven wave modes. Additionally, they demonstrated a deviation from the linear model which they ascribe to finite dust temperatures.

The DAW investigations published in [21, 22] were based on the results of experiments performed on board the ISS in the PKE-Nefedov set-up [8].

In this work, we address investigations of externally excited nonlinear DDWs performed for the first time in the PK-3 Plus set-up on board the International Space Station (ISS), a new advanced installation with unique properties [27].

2. Experimental set-up and observation conditions

The capacitively coupled plasma chamber of the PK-3 Plus set-up on the ISS can operate with argon and neon plasmas at pressures between 5 and 250 Pa and powers between 0.01 and 1 W. Melamine–formaldehyde (MF) microparticles of six different sizes between 1.55 and 14.9 µm diameter can be inserted into the chamber, and an additional low frequency modulation frequency between 1 and 255 Hz with a maximal amplitude of ±55 V can be applied to the electrodes.

In the experiment described in this paper, the chamber was filled with neon gas at a pressure of approximately 16 Pa with a small symmetrical gas flux. The peak-to-peak RF voltage applied between the electrodes was typically 46 V at a discharge power of about 20 mW. For the duration of the experiment, the gas flux was stopped. After igniting the discharge, monodisperse MF particles with a diameter of 9.2 µm and a density of 1510 kg m⁻³ were inserted into the plasma. The particles were illuminated from the side with a vertically extended laser sheet, the scattered light of which was recorded with a CCD camera at a frame rate of 50 Hz. (We will term the direction which is perpendicular to the electrodes ‘vertical’, and correspondingly, the direction which is parallel to the electrodes will be called ‘horizontal’.) A small temperature gradient between the top and bottom electrodes of 3 K m⁻¹ was applied, pointing towards the upper electrode. A sketch of the experimental set-up and further details can be found in [27].

The field of view was 35.7 mm × 26.0 mm, and the spatial resolution was 49.6 µm pixel⁻¹ (45.05 µm pixel⁻¹) in the horizontal (vertical) direction.

In addition to the RF voltage, a variable modulation voltage with frequencies between 1 and 48 Hz was applied to the electrodes. The frequency steps were varied from 0.5 for small frequencies to 3 Hz for high ones, so that the analysed frequency bands were: 0–7 Hz with a step of 0.5 Hz, 7–21 Hz with a step of 2 Hz, and 21–48 Hz with a step of 3 Hz.

In order to achieve a response of the system as linear as possible, the modulation amplitude A in the region between 1 and 9 Hz was varied as

\[ A = A_{\text{max}} \left( f_{\text{mod}} / f_{\text{max}} \right), \]

where \( A_{\text{max}} = 13.2 \) V, \( f_{\text{mod}} \) is the modulation frequency and \( f_{\text{max}} = 9 \) Hz. Above 9 Hz, the modulation amplitude was kept constant.

In doing so, we guess that the variation of the excitation amplitude affects mainly the intensity of the oscillations rather than the wave dispersion. Nevertheless, this does not allow us to distinguish the effects caused by modulation of the amplitude from those caused by modulation of the frequency in the region below \( f_{\text{mod}} = 9 \) Hz. However, as characteristic changes also take place when the amplitude is kept constant, we believe that the effects
Figure 1. Snap shots of particle distributions at different modulation frequencies: (a) the breathing mode with weak horizontal waves (0 Hz); (b) the slashing mode and the initial stage of vertical wave-ridges (3 Hz); (c)–(e) stages of oblique waves: initial intensification and bending of the wave ridges (5 Hz), the wave activity involves all the cloud (11 Hz), and final stage with spatially separated horizontal and vertical wavefronts (15 Hz), (f) high frequency mode (24 Hz). Note a local constriction of the cloud clearly seen at stages (d)–(f), indicating a separation of circulation zones.

described below are caused mainly by changing the modulation frequency. At least for $f_{\text{mod}} > 9$ Hz, this assumption is certainly true.

3. Observations

Figure 1 shows configurations of the complex plasma during various external modulation frequencies.

Without any external excitation (figure 1(a)), the plasma is relatively stable. Almost in the centre of the system, there is a void (particle free region, see [28]) present. The particle cloud is a little bit asymmetric: more particles concentrate in the region below the void than above it, and the bottom part is visibly wider. This is due to the present temperature gradient (see section 2).

The cloud is weakly ‘breathing’ (i.e. oscillates almost radially with respect to the geometric centre) at a frequency $\simeq 5$ Hz. The particles closest to the lower electrode oscillate almost vertically. Only in the far left part of the system there are some weak self-excited waves present, which can be observed without any external excitation. The breathing mode may be initiated by a weak heartbeat type instability [29, 30].

With external excitation, at first the cloud starts to oscillate at the frequency of the applied modulation (the so-called ‘slashing mode’, figure 1(b)). Then, at modulation frequencies higher
Table 2. Observed phases of the cloud dynamics for various modulation frequencies.

| $f_{\text{mod}}$ | Localization | Observations |
|------------------|--------------|--------------|
| 0 Hz             | Left         | Weak horizontal waves, weak horizontal oscillations |
|                  | Bottom       | No waves; weak vertical oscillations |
|                  | Oblique      | No waves; breathing-type oscillations |
| 1.0–3.5 Hz       | Left         | Horizontal waves, vertical oscillations at $f_{\text{mod}}$ |
|                  | Bottom       | Vertical slashing mode at $f_{\text{mod}}$ |
|                  | Oblique      | Vertical flashing mode at $f_{\text{mod}}$ |
| 3.5–9.0 Hz       | Left         | Horizontal waves, vertical oscillations with $f_{\text{mod}}$ |
|                  | Bottom       | Vertically propagating nonlinear ridges |
|                  | Oblique      | Nonlinear oblique waves |
| 9.0–15.0 Hz      | Left         | Nonlinear horizontal waves |
|                  | Bottom       | Nonlinear vertical waves |
|                  | Oblique      | Nonlinear oblique waves completely connect the zones of dominantly vertical and dominantly horizontal propagation |
| 15.0–17.0 Hz     | Left         | Intense horizontal waves |
|                  | Bottom       | Intense vertical waves |
|                  | Oblique      | Weak oblique waves accompanied by high frequency slashing |
| 17.0–48.0 Hz     | Left         | Weak horizontal waves |
|                  | Bottom       | Attenuated vertical wave-ridges |
|                  | Oblique      | No waves |

than 3 Hz, vertical waves are excited in the bottom part of the cloud, and the horizontal waves in the left part of the cloud become stronger. This can be clearly seen in figures 1(b)–(d).

At the modulation frequency $f_{\text{mod}} \simeq 4.5$ Hz, the zone of actively propagating vertical waves is extended to the left and ‘oblique’ waves start to propagate inside the cloud. This behaviour has not been reported before: in [14], the oblique waves appeared spontaneously; in [22] the direction of the waves was caused by the fact that the modulation frequency was applied to the ring electrode only. In [21], no oblique waves were reported.

The zone of oblique waves are visible quite well in figures 1(c) and (d). At $f_{\text{mod}} = 9$ Hz, the zone of oblique excitations completely connects the vertical and horizontal ones.

It is worth noting that near the central part of the cloud, the oblique wavefronts are practically parallel to the void boundary, whereas in the left part of the cloud, they are parallel to the left cloud edge (the visible wave ridges are almost transverse with respect to the cloud). During the resonance, when the bottom and left waves are connected, the angle of the oblique waves changes with the distance from the void from horizontal below the void to vertical in the left part (see figure 1(d)). At higher modulation frequencies, no oblique waves are excited (figures 1(e) and (f)), and the zones of wave activity are disconnected again. The observed phases are shown in detail in table 2. A movie showing the particle cloud during the experiment is available online (http://www.mpe.mpg.de/~mschwabe/isswaves.html/).
Figure 2. The particle cloud is shown as a superposition of ten images displaced in time by 0.24 s to demonstrate the location of wave zones and particle circulations (time interval 13.2–15.36 s). The field of view is 35.7 × 26.0 mm². Two intense vortices can be clearly seen in the left part and in the bottom right part of the cloud. The rectangles indicate the regions used in the wave field analysis: below the void (4, bottom), a middle part (3, oblique), and an edge region (1, left). The regions labelled (1), (3) and (4) were used to prepare figures 3 and 6. Figure 4 was based on an analysis of region (4). Figure 7 shows results related to region (3). We also used an extended narrow stripe labelled (2) to prepare figure 11. The arrows indicate dominant directions of observed wave propagation.

4. Analysis techniques

4.1. Periodgrams

We analysed three regions of the plasma cloud thoroughly, one directly below the void (this part we will refer to as ‘bottom’), one in the left corner of the particle cloud (which will be called ‘left’), and the region immediately to the left of bottom, where the waves were propagating obliquely (‘oblique’ region). Figure 2 shows the locations of these regions. A narrow part of the left region was also extended to the void.

We determined the mean distances between the particles by finding the first peak in the pair correlation function when no modulation frequency was applied. From the distances we calculated the three-dimensional densities \( n_d = 3\Delta^{-3}/4\pi \) as \( n_d = (5.6 \pm 1.1) \times 10^9 \text{ m}^{-3} \) (left region), \( n_d = (8.7 \pm 3.2) \times 10^9 \text{ m}^{-3} \) (oblique region) and \( n_d = (16 \pm 7) \times 10^9 \text{ m}^{-3} \) (bottom region).

We then plotted ‘periodgrams’ as in [22, 24] for these regions by adding up the measured pixel intensities for every wave position along the propagation direction. Thereafter the resulting function is plotted for every frame. In some senses, this procedure is equivalent to averaging, allowing us to reduce statistical errors. For instance, for the bottom region (region 4 in
Figure 3. Top: periodgrams of vertical (a), horizontal (b) and oblique (c) waves observed during the experiment. For the sake of convenience the investigated frequency band is divided into three parts: (1) 0–4.5 Hz, (2) 5–15 Hz and (3) 17–48 Hz. The rulers at the sub-band bottoms show the time counted from the start of the experiment. The regions marked in bold atop the band indicate the parts which were analysed. Bottom: enlarged bottom, left and oblique regions (initial phase without external excitation). The shown spatial scales are the same for (1a)–(3a), (1b)–(3b) and (1c)–(3c), respectively.

Figure 3 shows the periodgrams obtained this way for all three regions. Brighter regions correspond to higher particle number densities.

We determine the oscillation frequencies of the particles in several ways (see also section 6). One set of data was obtained directly from the periodgrams (figure 3) by correlation analysis, similar to [24].

Then, by determining the slope of the brightest strips of the periodgrams, we measure the phase velocity of the waves.

The observed particle behaviour (as described above in section 3) is clearly visible in the periodgrams shown in figure 3. For instance, the motion of the bottommost rows oscillating even without external excitation is represented at the top left part of this figure 3(1a), while horizontal waves are observable as bright stripes with a distinct angle in the slopes in the same frequency domain (figure 3(1b)). In figure 3(1c) some new structures appear when the external modulation is started, which are due to the vertical component in the oblique cut (region 3, figure 2). Oscillations of the whole cloud in the domains with a low excitation frequency (1–2 Hz) are nicely visible in figures 3(1a) and (1c). The horizontal waves shown in figures 3(1b), (2b)
and (3b) (observed in region 1, figure 2) do not change periods and slopes for a long time in contrast to the vertical oscillations shown in figures 3(1a), (2a) and (3a).

In figures 3(1c) and (2c) the regular bright strips in the right part of the diagram, corresponding to the wave ridges travelling through the cloud, do not appear until the excitation frequency rises to 3.5 Hz.

At higher frequencies, the oblique waves disappear (starting at the end of figure 3(2c)), vertical waves occupy only the narrow stripe of the cloud (figure 3(3a)), whereas horizontal waves (still with approximately the same constant period) are clearly seen in figure 3(3b).

4.2. Particle tracks

Another way to determine the oscillation periods is to analyse the particle tracks. We determine the particle positions in a standard way as described, for example, in [31]. Examples of periodgrams calculated by using the tracked particle positions and those calculated with the help of the pixel intensities are shown in figure 4. The positions of wave ridges indicated by both methods agree well with each other.

For the edge regions 1 and 2 (‘left’ in figure 2), it was possible to compare results of measurements obtained by using periodgrams with those calculated by fast Fourier transforms (FFTs) of the particle velocities. In doing so, we first calculated the velocities for every particle track (see section 6), then subtracted the mean value, applied a Hann window and finally Fourier-transformed the result. Then we identified the most intense peaks and determined the corresponding frequencies.

Using FFTs was only feasible for these two regions because there particle tracks are long enough. The tracks analysed in other regions are shorter, which does not allow us to obtain a reasonable resolution. The method of using FFTs has the advantage that several peaks in the frequency spectrum can be detected simultaneously (see, e.g. figure 5 below).

4.3. Measurement errors

For our proposed routines of measurements we have several possible sources of errors: pixel noise, pixel locking and poor statistics (see [24]).
We estimate the error induced by pixel noise by tracking an agglomerated particle lying immobile on the lower electrode. The maximal resulting error in the position was measured to be of the order of 0.1 pixels.

The error of velocities and forces (see section 6) coming from this uncertainty is estimated as 7%. The error in the determined particle positions is about 1%.

To estimate errors caused by the fluctuating plasma background, we inspected a particle-free stripe (35.1 mm × 0.45 mm) in our images. The maximal expected error from this source is of the order of 1%.

We minimized the pixel locking effect by choosing suitable parameters for tracking, in a similar way as described in [32].

The largest uncertainty stems from statistical variations of the data we used for measurements. To determine a mean value of a measured parameter (oscillation frequency, cloud edge position, mean particle velocities, etc), we either calculated the mean and corresponding standard deviation, or, if the number of measurements was high enough, plotted all determined values of this parameter and then fitted a Gaussian to the result. The resulting standard error is shown in the corresponding plots. For instance, for oscillation frequencies the error determined this way usually was of the order of 10% or less.

The expected total error, hence, is of the order of 13%.

5. Wave parameters

The spectrum of waves and oscillations observed in the course of the present experiments is surprisingly rich. Of course, it was expected at once to register DAWs (or DDWs) because these waves were observed in a number of previous studies. We also expected to maybe find traces of a slashing mode, since in our experimental conditions it was possible to trace trajectories of individual particles. (The particles were compelled to shake with the applied periodic modulation.)

Even from first sight of the diagrams shown in figure 3, it is clear that the situation is much more complicated. At once, it is possible to distinguish the global modes (breathing and slashing modes, figure 3(1a)) and the local modes. The latter are the ‘sound-like’ nonlinear modes (figures 3(2c) and (3c)), the spatial and temporal periods of which grow with the modulation frequency, and the mode in the left part of the cloud the period of which is quite constant and practically independent of perturbations (figures 3(1b), (2b) and (3b)).

Figure 5(a) shows a periodgram obtained from average horizontal particle velocities without external modulation. The particle velocity field was binned in the horizontal direction (bin size 0.06 mm). The analysed region corresponds to the left region 1 in figure 2, but is a bit narrower and extended approximately double towards the cloud centre to enlarge the analysed field of global oscillations. The propagating waves (0 ≤ x ≤ 4 mm) are clearly visible as inclined lines. The vertical lines indicate the global oscillation of the whole cloud without propagation. Figure 5(b) shows the logarithm of the corresponding Fourier spectrum. It was produced by subtracting the mean values from the data, applying a Hann window and then Fourier-transforming the data, as described in section 4.2 above. The frequency of the horizontal oscillation, which is approximately 5 Hz, and one of its harmonics cover the whole analysed space. The frequencies of the propagating waves near the left end of the cloud (small x values) are visible as bright red spots in the corresponding region. They are smaller than the frequency of the global oscillation.
Figure 5. (a) Periodgram of the average horizontal particle velocities in an extended left region \((12.4 \times 2.7 \text{ mm}^2)\). To enhance the contrast we use a grey-scale in the interval \((-1.0, 1.5) \text{ mm s}^{-1}\); all values \(v \geq 1.5 \text{ mm s}^{-1}\) are shown in white, whereas all \(v \leq -1.0 \text{ mm s}^{-1}\) are shown in black. The wave propagation in the region \(x \leq 4 \text{ mm}\) and global oscillations of the cloud are clearly seen. (b) Fourier spectrum of individual bins in the same region. The colour indicates the logarithm of the intensity of the spectrum in arbitrary units, where values \(\log(\text{Power}) \geq 1.0\) are shown in red and values \(\log(\text{Power}) \leq -1.6\) are shown in blue.

Figure 6 shows the oscillation frequencies which we determined using the periodgrams in figure 3 with the three different analysis methods: (a) periodgrams, (b) direct analysis of particle tracks and (c) FFTs of particle tracks. With the help of the FFTs, several peaks for one modulation frequency were detectable, sometimes showing harmonics of the primary frequency and making possible a simultaneous following of the modulation frequency and the wave frequency in quite a wide range of \(f_{\text{mod}}\).

Superimposing the results of the three methods shows good agreement between them. Only in the bottom region, where \(5 \text{ Hz} \leq f_{\text{mod}} \leq 8 \text{ Hz}\), the frequencies of the particles oscillating vertically determined by analysis of the particle tracks are a little higher than expected from the data obtained with the periodgrams. This may be due to some systematic measurement errors arising from the peak picking procedure during the analysis of the particle tracks (figure 6(b)).

The frequency of horizontal waves (left edge of the cloud) remains more or less constant at a level of 4.5 Hz.

Initially in the oblique and bottom parts of the cloud (figure 2) there are no propagating waves, only oscillations take place. The frequencies of oscillations \(f_{\text{os}}\) are equal to the modulation frequency. This corresponds evidently to a vertical slashing mode.

Vertically propagating wave-ridges start up at \(f_{\text{mod}} = 3 \text{ Hz}\) with the oscillation frequency 2 Hz. The wave frequency gradually grows up to approximately 3.5 Hz while the modulation frequency grows up to \(f_{\text{mod}} = 10 \text{ Hz}\). Then the wave frequency varies only a little up to \(f_{\text{mod}} \approx 25 \text{ Hz}\), where it drops down to 3 Hz. Later on it remains nearly constant again. We do not have enough data to study this ‘frequency drop’ in more detail.

For the oblique waves, the situation is similar, with the only difference that they were never observed at modulation frequencies higher than \(f_{\text{mod}} \approx 20 \text{ Hz}\).
Figure 6. (a) Oscillation frequencies versus modulation frequency for the left (red crosses), bottom (black squares), and oblique (blue triangles) regions obtained by using the pixel periodgrams shown in figure 3. (b) Oscillation frequencies obtained by analysing the particle tracks directly (red crosses: left region, horizontal movement; green triangles: left region, vertical movement; black squares: bottom region, vertical movement). (c) Frequencies determined with FFTs of the particle tracks (red crosses: left region, horizontal movement; green triangles: left region, vertical movements). The analysed regions are those indicated in figure 2. The dashed lines indicate points of equal frequencies $f_{os} = f_{mod}$.

We can estimate the charge of microparticles assuming that the horizontal waves in the left region oscillate at the dust plasma frequency

$$\omega_{pd} = 2\pi f_{pd} = \sqrt{\frac{Ze^2n_d}{m_d\epsilon_0}},$$

(2)
where $m_d$ is the mass, $Z$ is the charge and $n_d$ is the number density of the microparticles. Setting $f_{pd} = 5$ Hz, $m_d = 6.2 \times 10^{-13}$ kg and $n_d = 5.6 \times 10^9$ m$^{-3}$ (density determined for the left region, see above), we find $Z \approx 6200$.

This estimate is well inside the range predicted by drift motion limited theory [33] if the electron temperature is 4 eV and the electron density is of the order of $(1 - 3) \times 10^{13}$ m$^{-3}$. For comparison, radial motion theory [34, 35] results in a charge of $Z \approx 1300$ and orbit motion limited theory [36, 37] in $Z \approx 14000$ for the same set of parameters.

5.1. Phase velocities and spatial periods

The phase velocity of vertical waves (region 4, bottom) is always $\approx 4$ mm s$^{-1}$ as we determined from the periodgrams. Only in the interval $3$ Hz $\leq f_{mod} \leq 5$ Hz and starting from $f_{mod} = 25$ Hz, the phase velocity is $\approx 5$ mm s$^{-1}$. The mean value is $4.4 \pm 0.4$ mm s$^{-1}$.

The phase velocity of oblique waves varies from 7 to 3 mm s$^{-1}$ with an average value of $5.8 \pm 0.8$ mm s$^{-1}$. It can be seen that the velocity is almost constant in figure 3(2c).

The velocities of horizontal waves in the left region are $6.5 - 7$ mm s$^{-1}$ with an average of $6.8 \pm 0.1$ mm s$^{-1}$. The wavelengths of these waves are around 1–2 mm almost for all modulation frequencies.

5.2. Oblique quasi-sound wave (OQSW)

The wavelength of the waves propagating in the oblique region 3 (figure 2) visibly varies with the modulation frequency. We can plot, hence, this as a kind of ‘dispersion relation’ [22]. This relation is shown in figure 7, and it is a quasi-sound-like type because of an almost constant

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**Figure 7.** Wavenumber measured in the oblique region (figure 2 region (3)) using the periodgram as a function of the angular modulation frequency (black squares). The fit (black dashed line) is a least-squares fit running through zero. For reference, the data measured in [22] (red triangles) and a line corresponding to the mean of the slopes given in [22] (red dotted line) are also shown.
Figure 8. Averaged positions of the vertical cloud edges versus modulation frequency. Solid lines: outer edges, dotted lines: inner edges (void boundary), dashed line: centre of the chamber. Note especially a 15% compression of the cloud in the oscillatory field, which is caused by the change of the modulation amplitude according to equation (1).

slope corresponding to the velocity of $14 \pm 3 \text{ mm s}^{-1}$. We can thus call these waves OQSWs. For comparison the data obtained in [22] is shown in the same figure 7 (red triangles). For reference we also plot a line corresponding to the velocity of $21 \text{ mm s}^{-1}$, which is the mean of the velocities given in [22]. In [22], only that data is shown for which it is possible to fit a straight line passing through zero and which is sufficiently linear.

Note that we show in figure 7 the $k$ versus $\omega_{\text{mod}}$ dependence as has been previously recommended in a number of publications [10, 21, 22]. Note also that plotting the measured wavenumbers as a function of the measured wave frequencies still results in a rise with frequency. Fitting a linear regression line running through zero to this data yields a group velocity of $3.5 \pm 0.4 \text{ mm s}^{-1}$, which is much closer to the values we measured using the periodgrams (see section 5.1) than the value resulting from using the modulation frequencies.

6. Particle dynamics

6.1. Movement of the cloud and the void

We determine the boundaries of the particle cloud by plotting contours of the smoothed pixel brightness of every image. To do that, we first smoothed the image and then selected pixels with a brightness $\geq 35$. The result is shown in figure 8.

As is clear from figure 8, both the cloud size and the size of the void decrease monotonically as the modulation frequency increases in the range $f_{\text{mod}} \leq 10 \text{ Hz}$. This is caused by a change in the amplitude of the modulation as given by equation (1).

Without external modulation, the cloud width is 13 mm, it is then compressed up to 11 mm. The void is compressed more than the whole cloud. In the beginning the width of the void was 75% of that of the cloud. At $f_{\text{mod}} \geq 10 \text{ Hz}$, it is less, 60–65%.
Figure 9. Particle vibrations and transport at the cloud edges. Shown are two panels ((a): modulation frequency 2 Hz, (b): 4 Hz), each of them consists of ten superimposed consecutive images, which are colour-coded (the colour varies from red, orange, yellow, green, blue to purple). Enhanced particle oscillations at the periphery are shown as long bent multicoloured lines. This demonstrates that these particles are moving faster compared to ‘bulk’ particles during the observation time of 200 ms. There also are noticeable clockwise/counterclockwise (top/bottom) circulations (indicated by arrows). The circulation accelerates at higher modulation frequencies.

At lower excitation frequencies particle oscillations are clearly distinguishable at the outer edges of the cloud. The void boundary also oscillates approximately with the same frequency and phase, but with a much smaller amplitude.

At higher $f_{mod}$, the amplitude of the oscillation of the void boundaries decreases faster than that of the cloud edges.

6.2. Individual particle tracks

The particle behaviour is rather simple under our conditions. When the wavefront approaches a particle, it is captured by the wavefront and moves within it for some short time. Then the particle leaves the wavefront, trying to relax to its original quasi-equilibrium position. When the new wavefront arrives, this circle starts over. This procedure is similar to that observed and described in [24]. The periodic or quasi-periodic motion is combined with vertical oscillations forced by external modulation.

Figure 9 shows superimposed particle positions in ten consecutive frames corresponding to the left edge of the cloud at modulation frequencies of 2 and 4 Hz.

In both cases the tracks near the border of the cloud get longer. This means that in both cases the particles accelerate towards the edge.

In the bulk of the cloud the general trend is to move to the left, meaning from the void towards the edge. Inside a narrow surface layer, there is an opposite trend: the particles move...
Figure 10. Vector maps of particle velocities (1) and force fields (2) at the cloud periphery for four different instants of time: (a) 23.50 s, (b) 23.58 s, (c) 23.66 s and (d) 23.74 s. The modulation frequency was 2 Hz (compare figure 3). The nonlinear waves form visible multi-ridge patterns. The additional colour-coding helps to observe the variation of the magnitude of the forces and velocities with position.

upwards to the right and downwards to the right (hence, in the direction of the void), which is also clearly visible in the figure. This shows that a ‘circulation dynamo’ works in the cloud (as in [7] but more complicated in nature): the top part rotates clockwise, whereas the bottom part rotates anticlockwise.

From the particle tracks, we calculated the velocities (using second-order extrapolation for the first and last points of the tracks). An example is shown in figure 10. The velocities are of the order of a few millimetres per second. The propagation in wavefronts is clearly visible, and so is the rise in magnitude of the velocity the further left the particle is situated. The sequence shown in figure 10 covers approximately half a vertical period, which is also visible in the vertical orientation of the vectors.

6.3. Forces acting on the particles

We calculated the net force \( F_{\text{net}} \) acting on the microparticles using the velocity \( v_d \) and acceleration \( a_d \) which we determined from the particle tracks:

\[
F_{\text{Ep}} + F_{\text{net}} = m_d a_d,
\]

where \( F_{\text{Ep}} \) is the Epstein drag force \([38]\)

\[
F_{\text{Ep}} = -\gamma m_d v_d = -\delta_{\text{Ep}} \frac{4\pi}{3} n_n m_n u a_d^2 v_d.
\]

Here \( \gamma \propto 1/r_d \) is the damping rate coefficient, \( n_n \) is the number density of the neutral particles, \( m_n \) and \( u_n = \sqrt{8kT_n/\pi m_n} \) are their mass and thermal velocity (we assumed a temperature of \( T_n = 300 \) K in the calculations), \( r_d \) is the radius of the microparticles and \( m_d \) is their mass. \( \delta_{\text{Ep}} \) is a coefficient which depends on the interaction of the microspheres with the gas atoms.

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Figure 11. (a) Number $n$ of particles in the slab (2.7 mm high and 0.3 mm wide), (b) mean particle velocity $v$ and (c) mean force $F$ acting on the particles in a central region extending from the left cloud edge to the void (region 2 in figure 2) as a function of the horizontal position, smoothed over a width of 250 µm. We overplotted the data of five frames in the same phase during a modulation of 2 Hz, assuming a wave frequency of 4.2 Hz. The error bars in the velocity and force correspond to the propagated error in the position measurement.

Konopka [31] measured $\delta_{Ep} = (1.48 \pm 0.05)$ s$^{-1}$ for melamine–formaldehyde spheres in argon and krypton by analysing horizontal oscillation of particles. This value is close to that theoretically derived by Epstein [38] for diffuse reflection with accommodation on a thermal non-conductor. It also agrees with one of the two values measured in [39] (the one measured with the vertical resonance method) within the uncertainty range. In our calculations, we therefore use $\delta_{Ep} = 1.48 \pm 0.05$ s$^{-1}$, which results in a value of $\gamma = 15.5$ s$^{-1}$ under our conditions. Using the other value measured in [39], $\delta = 1.26 \pm 0.13$ s$^{-1}$, results in a 15% smaller value of the Epstein drag force.

Figure 10 shows the forces acting on the particles in the left part of the cloud as vector maps. Note the displacement of the wave ridges in forces compared to that in velocities.

The force is of the order of $10^{-13}$–$10^{-14}$ N, which is 1/10 to 1/100 of the strength that gravity would have on the microparticles on Earth. The periodic rise and fall corresponding to the waves and the fall-back to the original position of the particles is clearly visible.

Figure 11 shows the mean densities, mean velocities and mean forces acting on microparticles in a slab extending from the left edge of the cloud to the void in one phase of the horizontal waves as function of the horizontal position. As in figure 10, the peak in velocity is displaced compared to the peak in force, so that first the forces act on the particles, which are as a result accelerated to their highest velocities.

In the region close to the void, the forces are also higher than in the bulk of the plasma. The variation in particle density corresponding to the wave ridges is also visible.
7. Conclusion

We investigated dust density waves which were externally excited in a complex plasma under microgravity conditions on board the ISS. Additionally to the vertical oscillation with the externally imposed frequency, we observed propagation of waves both in vertical and horizontal direction. The frequency of the horizontal oscillation did not depend on the external modulation frequency, in fact, the horizontal waves were present even before the modulation was started. The frequency of the vertical waves showed some dependence on the modulation frequency.

When the modulation frequency was in the range of that of the horizontal oscillation, the vertically propagating waves started spreading towards the left part of the cloud and propagated also obliquely compared to the direction defined by the electrodes. We determined the wavenumber as a function of the modulation frequency for those OQSWs.

Around a modulation frequency of 9 Hz, the waves filled the whole cloud. At higher frequencies, the oblique waves disappeared again, and the system returned to the previous state.

Additionally, we also investigated the particle dynamics and determined velocities and net forces acting on the particles.

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