How particles move in nonlinear acoustic waves?

Lin I (伊林)
Chen Ting Liao (廖振廷), Chen Yu Tsai (蔡承祐), Lee Wen Teng (鄧力文)
Department of Physics
National Central University
lini@phy.ncu.edu.tw

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Acoustic wave in gas
A linear perturbation fluid picture

Lagrangian picture at the kinetic level?
Longitudinal density waves:

- Acoustic waves in solid, liquid, and gas
- Electrostatic waves in plasmas
- Dust density wave in dusty gas
- Dust density wave in dusty plasma

Micro-motion of particles in longitudinal density waves?
Wave-particle micro-dynamics?

Particles interact with and constitute the wave

Coherent wave field & particle-particle interaction

Particle motion
Trapping and surfing in a traveling wash-board field

A continuous mean field approach

Effect of spatio-temporal heterogeneity at the discrete level?

How particles constitute and sustain the propagating wave?
Dust acoustic wave in a dusty plasma
Wave-particle micro-dynamics in self excited dust acoustic waves

Our studies

Lagrangian picture through direct particle tracking using high speed CCD

• Nonlinear particle oscillation in waves
• Wave-particle interaction
• How particles sustaining the propagation of waves
• Anisotropic Non-Gaussian wave-particle heating

From regular to turbulent wave
Dusty plasma
Charged fine particles suspended in low pressure gaseous plasma

- Interstellar plasma
- Space plasma
- Laboratory discharge

Spokes in Saturn rings

Dust cloud in a plasma etcher

G.S. Selwyn, et al., APL 57, 1876 (1990)

Charging and suspension of dust particles in a laboratory discharge

$q = 10^4 \text{e}$
From the gas state to the crystal state
A bridge from plasma to condensed matter

- Micro-transport
- Defect dynamics
- Confinement induced layering and slow dynamics
- Visco-elastic response
- Shear induced heating
- Few body cluster
- Chain bundle liquids
Dust acoustic waves (DAW) in dusty plasmas

**DAW**

- Longitudinal wave with dust density and dust particle oscillations
  
  - Interplay of inertia, Coulomb interaction, ion streaming, dust charging and unfrozen ionization

**Previous studies**

Dispersion relation and various mechanisms using continuous macroscopic approaches
Our system

- \( P \approx 200 \text{ mTorr Ar} \)
- particle diameter: \( 5 \, \mu \text{m} \)
- \( Q/\text{particle} \approx 10^4 \text{ e} \)
Turning on self-excited DAW by increasing rf power or decreasing pressure

Contour plot of $n_D(z,t)$ - dust density evolution

$V_p = 50$–$80$ mm/s

$n_D$ (arb. unit)

$z$ (mm)

4–5 mm

X 20 slow play
Dust density evolution at different heights

$\eta_b$

$0$

$500$

$1000$

time (ms)

$0$

$6$

$8$

$Z$ (mm)

$0$

$100$

time (ms)

$0$

$2$

$4$

$6$

$8$

$Z$ (mm)

$0$

$25$

$50$

$75$

$100$

$f$ (Hz)

$100$

$10$

$1$

$100$

$Run I$

$f_0 = 16 \text{ Hz}$

$v_p = 50 - 80 \text{ mm/s}$
Particle motions in a DAW

- **Upper region:**
  Small amplitude limit cycle oscillation
  Keeping dusts in the liquid state
Particle motions in a DAW

- **Middle region:**
  - Large amplitude chaotic oscillation
  - Turning dusts into the gas state

Escalating oscillation followed by long distance downward crest acceleration
Particle motions in a DAW

- **Lower region:**
  Middle amplitude **chaotic oscillation**
Particle motions in a DAW

Wiggling induced by local dust interaction
Why chaotic oscillation?
Why long distance downward acceleration?
Wave resonance acceleration?
Trough trapping?
How particles constituting and sustaining the propagating wave?
Why waveform steepening?
Crest trapping: moving with the crest
How does the wave propagate?

Accumulation  Depletion

Trough trapping has not been observed!
Waveform steepening

\[ n_d \]

ime (ms)
From regular to turbulent DAW

Regular (170 mTorr, 2.4 W)

Turbulent (170 mTorr, 3.4 W)
More chaotic trajectories in turbulent DAW

Trough trapping

1/20 slow play
Crest annihilation and recombination in turbulent DAW

Wave crest annihilation

Wave crest recombination
DAW induced non-Gaussian heating
Turbulent

Anisotropic non-Gaussian heating

$T_d \sim 250$ eV
Pulsed laser induced dusty plasma bubble and solitary wake field
Supersonic bubble in dusty plasmas

Strong localized density perturbation

60 Hz sampling rate

Hong Yu Chu and Lin I
PRL 90, 075004 (2003)
Collapsing bubble at high pressure

Quiescent DPL

<table>
<thead>
<tr>
<th>Damped Bubble</th>
<th>Traveling Bubble</th>
<th>Self organized dust density wave</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>II</td>
<td>I</td>
</tr>
<tr>
<td>193</td>
<td>170 163</td>
<td>150</td>
</tr>
<tr>
<td>P (mTorr)</td>
<td></td>
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</tbody>
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Collapsing bubble at high pressure
Summary

• Micro-motion in self-excited DAW and laser induced bubbles

• Melting from the liquid to the gas state with cyclic to chaotic particle oscillation as wave amplitude increases

• Wave crest trapping inducing chaotic motion

• Further trough trapping for the turbulent wave

• Anisotropic non-Gaussian heating by waves

• Supersonic bubble with dust depletion
Thank You