Measurements of Finite Dust Temperature Effects in the Dispersion Relation of the Dust Acoustic Wave

Senior Honors Thesis
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Erica Snipes
• What is a plasma?
• What is a dusty plasma?
• Previous work with dust temperature and Dust Acoustic Wave
• Experimental set up
• Experimental methodology
• Results
• Future Work
Solid

Neutral Particle

Increasing Energy

Organized
Strong intermolecular bonding
Coulombic forces
Short range
Liquid

Increasing Energy

Loosely organized
Collisions and weak intermolecular forces
Weak coulombic forces
Short range
Gas

Solid → Liquid → Gas

Neutral Particle

Increasing Energy

No organization
Collisions only
Local interaction only
Plasma

Increasing Energy

No organization
Collisions and electromagnetic forces
Local and long range
Examples

Plasmas - The 4th State of Matter

- Magnetic fusion reactor
- Inertial confinement fusion
- Nebula
- Solar wind
- Solar corona
- Interstellar space
- Neon sign
- Fluorescent light
- Aurora
- Flames
- Lightning

Temperature (K):
- $10^2$ to $10^8$

Number Density (Charged Particles / m$^3$):
- $10^3$ to $10^{33}$
Dusty Plasma

- Dust particle moves through the plasma, collects ions and electrons from the surrounding plasma - acquires a net charge.

\[ I_{\text{total}} = I_{\text{electron}} + I_{\text{ion}} + I_{\text{see}} + I_{\text{thermionic}} + I_{hv} = 0 \]

- Charge-to-mass ratio
Why are they interesting?

- They’re prominent in the universe.

- Example of a complex, self-organized non-linear system that allows for direct visualization on the kinetic level via light scattering that provides a test bed for a wide range of phenomena.

- Relatively low charge to mass ratio
  - Introduces new collective phenomena (e.g., wave modes such as the dust-acoustic and ion-acoustic wave)
  - Relatively long time scales for phenomena
Dusty Plasma Examples

Eta Carina Nebula

Noctilucent clouds
Why are they interesting?

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  ♦ Relatively long time scales for phenomena
Mach Cone

- Dust particles arranged in a monolayer, with a few particles underneath.
- Disturbance of lower layer dust particles moving at supersonic speeds compared to the natural dust speed.
- Measuring opening angle tells information about size of dust particle creating cone.
- Expected to occur in Saturn’s rings, could help determine size of dust in rings.
Microgravity

- Can neglect effect of Earth’s gravity. Similar to eliminating first order terms.
- Other smaller forces are able to be observed.
- Parabolic air flight
- International Space Station
- Instability in center of plasma causes higher ionization of atoms, resulting in ions streaming out of void, pushing dust particles away.
- Dynamic equilibrium reached with charged dust pushing back in.
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• Relatively low charge to mass ratio
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Dust Acoustic Wave

- Low frequency, compressional mode of the charged microparticle component.
- Propagation involves dynamics of heavy particles with small charge-to-mass ratios.
- Moves on the order of a few cm/s. Frequencies on order of Hz.
Previous Work

- Examining the condition necessary for the onset of the dust acoustic wave.
- Theory accurately predicted the threshold condition, if the dust temperature was ~1/40 eV.
- Dispersion relationship for a horizontally propagating wave was measured by modulating the discharge current
- The temperature was found by fitting the measured dispersion relation to a fluid model for the wave mode.
- Dispersion relationship for a vertically propagating wave was measured by modulating the discharge current.
- The temperature was found by fitting the measured dispersion relation to a fluid model for the wave mode.
- Dispersion relationship for a horizontally propagating wave was measured by modulating the discharge current.
- The temperature was found by fitting the measured dispersion relation to a kinetic model for the wave mode.
Procedure

• Create a cloud containing a natural wave over a range of pressures
  ✷ Accomplished for neutral pressures ranging from 50 to 120 mTorr

• Drive wave by modulating current
  ✷ Capable of driving the wave mode over a range of neutral pressures, from 50 to 120 mTorr

• Measure dispersion relation
  ✷ Measured for neutral pressures ranging from 55 mTorr to 70 mTorr

• Fit dispersion relation to extract temperature
  ✷ Completed for $p = 64$ mTorr
Step 1

Generate the natural wave
Experimental Set Up

- Wittenberg University DUsty Plasma Experiment (WUDUPE)
  - 8 in Conflat Tee
  - Base Pressure
    - ~ 8 mTorr
- Experimental Conditions
  - DC discharge plasma
    - Argon gas
  - 50-120 mTorr
  - Silica spheres
    - $d = 3\pm1 \mu m$
    - $m \approx 31 \text{ pg}$
Experimental Sketch

Front View
- Upper Electrode (1” diameter)
- Plasma
- Dust Cloud
- Dust
- Dust tray
- Vacuum Chamber
- Chamber Wall

Top View
- Chamber Wall
- Plasma and Cloud
- Laser sheet
- CCD Camera
Driving the wave
Driving

- Apply a ripple to the discharge current (0.185 - 0.3 mA) at desired frequency (9 ≤ f ≤ 25 Hz)
- Couples to natural wave mode
- Take 600 image sequences at 30fps
Step 3

Measure dispersion relation
Finding Wavelengths
Calibration
## Experimental Parameters

<table>
<thead>
<tr>
<th>Dust Parameters</th>
<th>Experimental Parameters</th>
<th>Plasma Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_d = 1.5 \times 10^{-6} \text{ m} )</td>
<td>( I_{\text{discharge}} = 1.185 \text{ mA} )</td>
<td>( n \sim 1.35 \times 10^{14} \text{ m}^{-3} )</td>
</tr>
<tr>
<td>( \rho_d \sim 2500 \text{ kg/m}^3 )</td>
<td>( I_{\text{P-P, modulation}} = 0.24 \text{ mA} )</td>
<td>( T_i \sim 0.025 \text{ eV} )</td>
</tr>
<tr>
<td>( m_d = 3.5 \times 10^{-14} \text{ kg} )</td>
<td>( P = 64 \text{ mTorr} )</td>
<td>( T_e \sim 3 \text{ eV} )</td>
</tr>
<tr>
<td>( n_d = 3.03 \times 10^{10} \text{ m}^{-3} )</td>
<td>( )</td>
<td>(</td>
</tr>
<tr>
<td>( Z_d \sim 6750 \text{ eV} )</td>
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Pressure = 64 mTorr
Fit the dispersion relations
Theory

- Dispersion relation used in the work of Williams et al.:

\[
1 - \frac{\omega_p^2}{(\omega - ku_{io})(\omega - ku_{io} + i\nu_i^{eff})} - k^2v_{ti}^2 - \frac{\omega_{pe}^2}{(\omega + ku_{eo})(\omega + ku_{eo} + i\nu_{en})} = 0
\]

- Where is the dust temperature dependence?

\[
v_{td} = \sqrt{\frac{k_B T_D}{m_d}}
\]
Dispersion Relation With Fit

\[ \omega (\text{rad/s}) \]

\[ k (\text{cm}^{-1}) \]

- \( T = 1/40 \text{ eV} \)
- \( T = 315 \text{ eV} \)
Limitations

• To model the measured dispersion relation, fluid model was used.
  - breaks down at shorter wavelengths (i.e., longer wavenumbers), particularly at smaller values of the dust temperature
  - increasing role of collisions at higher neutral pressures can also limit the validity of the model.

• The charge ($Z_d$) computed using OML theory tends to be larger than observed in experiment - particularly at higher values of neutral pressure.
  - A reduced charge results in a smaller slope in the calculated dispersion relation and requires an even larger value of the dust kinetic temperature to match the experimental measurements.
Results
Conclusions

- Create a cloud containing a natural wave over a range of pressures
  - Done for pressures ranging from 50 mTorr to 120 mTorr

- Drive wave by modulating current
  - Driving for pressures ranging from 50 mTorr to 120 mTorr

- Measure dispersion relation
  - Measured for pressures ranging from 55 mTorr to 70 mTorr

- Fit dispersion relation to extract temperature
  - Fit for 64 mTorr
Acknowledgements

- Dr. Andrew Zwicker
- Dr. Jeremiah Williams
Modified Dispersion Relation

\[ 1 - \frac{\omega_{pi}^2}{(\omega - ku_{io})(\omega - ku_{io} + i\nu_{i}^{\text{eff}})} - k^2\nu_{ti}^2 - \frac{\omega_{pe}^2}{(\omega + ku_{eo})(\omega + ku_{eo} + i\nu_{e}) - k^2\nu_{te}^2} = 0 \]

where

\[ u_{\alpha 0} = \frac{q_{\alpha}E_{0}}{m_{\alpha}v_{an}} \quad \nu_{t\alpha} = \left(\frac{k_{B}T_{\alpha}}{m_{\alpha}}\right)^{1/2} \quad \omega_{p\alpha} = \left(\frac{n_{\alpha}q_{\alpha}^2}{\varepsilon_{0}m_{\alpha}}\right)^{1/2} \quad \nu_{en} = n_{n}\sigma_{en}\nu_{te} \quad \nu_{dn} = \frac{8\sqrt{2}\pi}{3} \left(1 + \frac{\pi}{8}\right) \frac{r_d^2 n_m m_n m_n v_m}{m_d} \]

\[ v_{i}^{\text{eff}} = \nu_{in} + \nu_{id} = n_{n}\sigma_{in}\nu_{ti} + \frac{m_d n_d}{m_i n_{io}} \frac{8\sqrt{2}\pi}{3} \left(1 + \frac{\pi}{8}\right) \frac{r_d^2 n_{io} m_i \nu_{ii}}{m_d} \left[1 + \frac{\beta_{T}\lambda_{D}}{2r_d} + \left(\frac{\beta_{T}\lambda_{D}}{2r_d}\right)^2 \right] \Lambda \]

\[ \lambda_{D} = \frac{\lambda_{D\alpha}}{\sqrt{\lambda_{De}^2 + \lambda_{Di}^2}} \quad \lambda_{D\alpha} = \sqrt{\frac{\varepsilon_{o}T_{\alpha}}{n_{ao}q_{e}}} \quad \beta_{T} = \frac{Z_{d}q_{e}}{4\pi\varepsilon_{0}\lambda_{D}T_{i}} \quad \Lambda = \int_{0}^{\infty} \exp\{-x\} \ln\left\{ \frac{2x + \beta_{T}}{2r_{d}x + \beta_{T}} \right\} dx \]

Probe Measurements

\[ I(V) = I_{sat} \tanh \left( \frac{V}{2T_e} \right) \]
OML Reduced Charge

\[ T = 315 \text{ eV} \]
\[ T = 775 \text{ eV} \]