First Test of Long-Range Collisional Drag via Plasma Wave Damping

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Outline

• Background
• Apparatus
• Damping of Plasma Waves
• Collisional Drag Damping Theory
• Mechanisms that Reduce the Drag
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Collisions in a Magnetized Plasma

Magnetized Plasma $r_c < \lambda_D$

short-range collisions $\rho < r_c$

long-range collisions $r_c < \rho < \lambda_D$

Long-Range collisions enhance cross-field diffusion, heat transport, and viscosity by orders of magnitude over classical predictions.


Long-Range Collisions

Magnetized Plasma $r_c < \lambda_D$

Diffusion radius

$$d \equiv \left[ \left( \frac{e^2}{\mu} \right)^3 / D^2 \right]^{1/5} \propto T^{1/5}$$

where $D$ is the velocity diffusion coefficient and $\mu$ is the reduced mass

short-range collisions $\rho < r_c$

long-range collisions $r_c < \rho < \lambda_D$

$$v = n\bar{v}b^2 \ln \Lambda$$

$$\ln \Lambda = \frac{4}{3} \ln \left( \frac{r_c}{b} \right) + 5.9 \ln \left( \frac{d}{\max[r_c, b]} \right) + 2 \ln \left( \frac{\lambda_D}{\max[d, r_c]} \right)$$

3D Boltzmann perp-to-parallel collisions

1D Boltzmann collisions $\rho < d$

1D Fokker-Planck collisions $\rho > d$

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IV Apparatus

- Penning-Malmberg Trap
- Mg$^+$ Plasma
- Rotating Wall (RW)
- Laser Cooling
- Probe Beams

$N \sim 2 \times 10^8$ ions $B = 2.96 \text{T}$

$L_p \sim 10 \text{ cm}$ $10^{-4} \text{ eV} \leq T \leq 1 \text{ eV}$

$R_p \sim 0.5 \text{ cm}$
Plasma profiles are “top-hat” density, rigid-rotors

Laser diagnostics can only detect the Mg^+
Impurity species are formed through ionization and chemical reactions with the background gas at a pressure \( P \approx 10^{-9} \) Torr.
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• **Damping of Plasma Waves**
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In a trapped non-neutral plasma, **Langmuir** waves are called **Trivelpiece-Gould** (TG) waves.

**Cold Fluid Theory**

\[ f_{TG} = f_p \frac{k_z}{\sqrt{k_z^2 + k_\perp^2}} \]

\[ f_{TG} \approx f_p \frac{k_z}{k_\perp} \quad \text{(for } k_z \ll k_\perp) \]

where \( k_z = \frac{m_z \pi}{L_{\text{eff}}} \) (standing wave)

\[ f_{TG} \approx 135 \text{kHz}\sqrt{n_7 \frac{m_z \pi}{L_{\text{eff}}} R_p \left[ \frac{1}{2} \ln \left( \frac{R_w}{R_p} \right) \right]^{1/2}} \]
Detected Wave Signal

Plasma wave is detected as the induced image charge on a confinement ring.

Time evolution of detected response is fit by overlapping sine waves, and the damping is the exponential decay of this amplitude.

\[ T = 2.7 \times 10^{-3} \text{ eV} \]
\[ f_1 = 26.05 \text{ kHz} \]

\[ \gamma = -132 \text{ s}^{-1} \]
Damping of the $m_z = 1$ Mode

Increasing the impurity concentration increases the damping for $T \leq 10^{-2}$ eV
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Drag Damping Theory

Basic Idea

Ions are accelerated by the wave electric field as $eE/M_s$ producing a disparity in the velocity of different species. Inter-species collisions then cause drag forces, which damps the wave.

Equation of Motion for Species $\alpha$

$$M_s \frac{dN_s}{dt} = eE - \sum_{s'} M_s v_{ss'} (v_s - v_{s'})$$

Zeroth Order in Collisionality

$$\delta v_s \approx \frac{ek_z \delta \phi}{M_s \omega}$$

Species Accelerated by Wave Electric Field

First Order in Collisionality

$$\delta v_s \approx \frac{ek_z \delta \phi}{M_s \omega} - i \frac{ek_z \delta \phi}{\omega} \sum_{s'} \frac{v_{ss'}}{\omega} \left( \frac{M_{s'} - M_s}{M_s M_{s'}} \right)$$

Collisions Between Species Damps the Wave
Relative Fluid Velocity of Mg$^+$ Isotopes

Measurements of the parallel velocity distribution coherent with the wave-phase

Heavier Mg$^+$ isotopes move slower in the wave electric field in agreement with theory

\[ \delta v_f^{(25)} = (4.1 \pm 1.1)\% v_f^{(24)} \]
\[ \delta v_f^{(26)} = (8.2 \pm 1.1)\% v_f^{(24)} \]
Drag Damping Theory

For radially uniform plasmas with weak collisionality ($\nu << \omega_{TG}$)

$$\gamma_{\text{drag}} = \frac{1}{4\alpha_p^2} \sum_s \sum_{s'} \left( \frac{M_{s'} - M_s}{M_s^2} \right)^2 \alpha_p^2 \nu_{ss'}$$

where

$$\nu_{ss'} = \sqrt{\pi n_s \bar{V}_{ss'} b^2 \ln \Lambda}$$

Collisional Slowing Down Rate

$$\gamma_{\text{drag}} = \frac{\sqrt{2\pi e^4}}{4 \sum_s \frac{n_s}{M_s}} \sum_s \sum_{s'} \left( \frac{M_{s'} - M_s}{M_s^2 M_{s'}^2} \right)^2 \left( \frac{M_s M_{s'}}{M_s + M_{s'}} \right)^{1/2} \frac{n_s n_{s'}}{T^{3/2}} \ln \Lambda$$
Collision Rate for a “dirty” Plasma

Long-range collisions dominate the collisionality in these magnetized plasmas

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Measurements vs. Theory

Drag damping theory is in quantitative agreement with the experimental results only when long-range collisions (solid curves) are included, exceeding classical collision calculations (dashed curves) by as much as an order of magnitude.
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Mechanisms that Reduce the Drag

**Centrifugal Separation**

Below $T \approx 10^{-3} \text{ eV}$, the species centrifugally separate radially. Reducing the overlap between the species will reduce the drag damping.

**Fluid Locking**

Below $T \approx 10^{-3} \text{ eV}$, the collisionality exceeds the wave frequency. Relative velocity between species is diminished by frequent collisions reducing the drag damping.
The maximum measured damping rate (arrows) occurs at higher temperatures as the plasma density is increased.

Similar quantitative agreement with theory assuming long-range collisions (solid curves) over a factor of 7 change in density.
Mechanisms that Reduce the Drag

Centrifugal Separation

Below $T \approx 10^{-3}$ eV, the species centrifugally separate radially.
Reducing the overlap between the species will reduce the drag damping.

Fluid Locking

Below $T \approx 10^{-3}$ eV, the collisionality exceeds the wave frequency.
Relative velocity between species is diminished by frequent collisions reducing the drag damping.
Warm Centrifugally Separated Plasma

Species remix on a diffusion timescale of about 500 ms
Above $T \approx 10^{-3}$ eV the drag damping is correctly modeled by a radial average over the species profiles. Centrifugal separation reduces the drag damping. Above $T \approx 10^{-3}$ eV the drag damping is correctly modeled by a radial average over the species profiles.

$M_s = (24, 25, 26, 19, 29, 32, 39, 43)$ amu

$\delta_s \sim (52, 9, 10, 16, 4, 4, 4, 1)$ %

$Z(T)$

$Z(10^{-4}) = 0.43$
Mechanisms that Reduce the Drag

**Centrifugal Separation**

Below $T \approx 10^{-3}$ eV, the species centrifugally separate radially. Reducing the overlap between the species will reduce the drag damping.

![Graph showing density distribution with $n_{Mg24}$, $n_{Mg25}$, and $n_{Mg26}$, indicating $r$ vs $n_0$ and $H_3O^+$ distribution.]

**Fluid Locking**

Below $T \approx 10^{-3}$ eV, the collisionality exceeds the wave frequency. Relative velocity between species is diminished by frequent collisions reducing the drag damping.

![Graph showing temperature vs sum of velocities with $\omega_1$, $\omega_2$, and $\omega_3$ at $Z_{1924}$, indicating $T$ vs $\sum V_{s,24}$.]
Damping of Higher Frequency Modes

\[ M_s = (24, 25, 26, 19, 29, 32, 39, 43) \text{ amu} \]
\[ \delta_s \sim (48, 9, 10, 20, 4, 4, 4, 1) \% \]

Damping is the same for higher frequency modes at \( T \geq 3 \times 10^{-4} \text{ eV} \)

Fluid locking occurs at lower temperatures for the higher frequency modes

\[ f_1 = 27.25 \text{ kHz} \]
\[ f_2 = 50.35 \text{ kHz} \]
\[ f_3 = 68.45 \text{ kHz} \]
Summary

- We presented measurements of the damping of Langmuir waves over four decades in temperature.

- At high temperatures $T \approx 0.5$ eV, Landau damping dominates. Quantitative agreement with Landau theory is obtained for small amplitude waves.

- For $T \leq 10^{-2}$ eV, the damping is caused by inter-species drag scaling as $T^{-3/2}$ and increasing with the abundance of impurities.

- First test of long-range collision theory, which increases the drag by an order of magnitude.

- The damping is reduced as the species centrifugally separate and the collisionality exceeds the wave frequency at $T < 10^{-3}$ eV.