Effects of Electron-Neutral Collisions on Propagation of Electron Plasma Waves

T. Kawabe,* Y. Kawai,* O. Saka,* and Y. Nakamura
Institute of Space and Aeronautical Science, University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan

and

John M. Dawson†
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
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The propagation of electron plasma waves was studied experimentally in the regime where electron-neutral collisions dominate. It was found that the effects of collision not only enhance the damping of the wave, but also increase the wave number for a given frequency. These results are compared with some theoretical models.

Most experiments on the propagations of small-amplitude electrostatic electron waves in a plasma may be divided into two cases: (i) in one dimension,[1] and (ii) with finite transverse dimension.[2] Experimental results for both cases correspond to linearized theoretical dispersion relations for electron waves in collisionless plasmas. There has been little work on a collisional case although some theoretical work has been done. In this paper we present studies on the effects of collisions between electrons and neutral atoms upon well-defined one-dimensional electrostatic electron waves. It has been found that the damping rate for the amplitude increases and the wavelength becomes smaller with increase of the collision frequency. These results are discussed with the aid of some theoretical models, and it is found that the "effective" collision frequency for the wave is larger than the collision frequency between the particles.

The experiment was performed using the space chamber[3] at the Institute of Space and Aeronautical Science, University of Tokyo (2 m in diameter and 4 m in length). Two pairs of plasma sources were set face to face at both ends on the axis of the tank. These consisted of mesh anode and hot bundles for the cathode (both 15 cm in diameter). The density and temperature of the plasma were measured by a Langmuir probe and are found to be homogeneous across the chamber. The plasma density n_e was in the range of $1.0 \sim 2.0\times 10^6/\mathrm{cm}^3$, and the electron temperature T_e was in the range of $3\sim 5$ eV, depending on the neutral gas pressure. As a result, the Debye length was about 1 cm. Most of the experiments were carried out in argon (helium was also used). The pressure of the gas in the chamber was varied from 1×10^{-5} to 1×10^{-3} Torr, while the electron density of the plasma was kept almost constant by adjusting the discharge current in both plasma sources.

An electrostatic electron wave was excited by a transmitter, which consisted of three grids 15 cm in diameter. The direction of the propagation was chosen perpendicular to the axis to avoid effects due to a small amount of electron beam current produced at the discharges in the plasma sources. A Faraday cup was used as a receiver; this was 10 cm in diameter and consisted of two mesh grids and a collector. The outer grids of the transmitter and the receiver were grounded.

A signal was picked up by another mesh grid and collector, and fed into a wide-band amplifier, and a balanced mixer as is usual.[3] The distance x between the transmitter and the receiver was varied from 7 to 80 cm by moving the position of the transmitter rather than the receiver; this was because the disturbance of the plasma, due to the transmitter, is much smaller.

The rf voltage applied on the transmitter grid was less than about 0.3 V peak to peak so that $e\varphi/kT_e < 0.1$, so that no nonlinear effects were expected to be observed. The frequency of the excited wave was changed from 8 to 26 MHz to cover the range of ω/ω_p from 0.9 to 2.0 (ω is the frequency of the excited wave, ω_p the electron plasma frequency).

Typical raw data as drawn by an X-Y recorder are shown in Fig. 1. The electron density and the wave frequency were the same for both these cases ($\omega/\omega_p \approx 1.3$); the argon pressure was (a) 2.8×10^{-4} Torr and (b) 1.1×10^{-4} Torr. It should be noted that the effects of electron-neutral collisions on the propagation of the wave are (i) to increase the damping of the wave and (ii) to decrease the wavelength with increasing collision frequency.

The dispersion relation is obtained by normalizing the real and the imaginary parts of the wave number by the Debye wave number for different

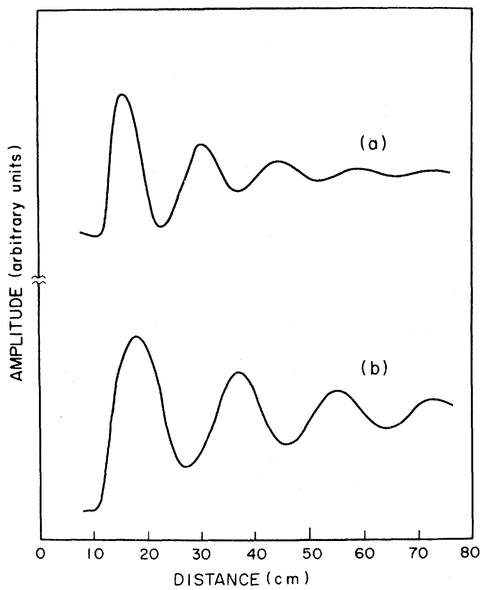

FIG. 1. Typical raw data for the wave propagations; for both, the frequency is 16 MHz, and the plasma frequency $\omega_p/2\pi \approx 12$ MHz. The argon gas pressures are (a) 2.8×10^{-4} Torr, and (b) 1.1×10^{-4} Torr.

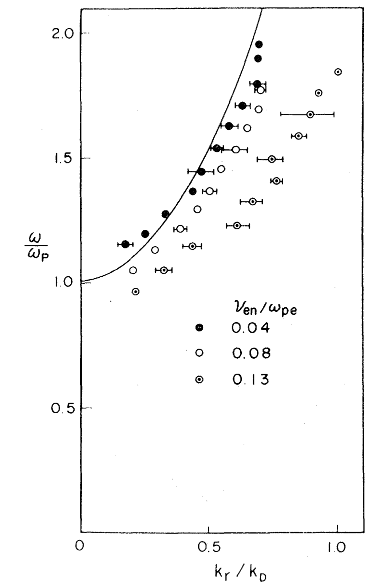

FIG. 2. Dispersion relations for the wave, where the normalized collision frequency is a parameter. Solid line, theoretical curve given by Eq. (1).

ω/ω_p, and is plotted as shown in Figs. 2 and 3. The collision frequency is calculated from the collision probability of electrons at the thermal velocity with argon atoms.[4]

Theoretically, the dispersion relation for an electrostatic electron wave in a collisionless Maxwellian plasma may be written as

$$1 = (\omega_p^2/k^2 v_e^2) Z'\omega/k v_e, \tag{1}$$

where v_e is the electron thermal velocity, and Z' is the derivative of the plasma dispersion function. This dispersion relation is solved numerically[5] for real ω and complex k; the real part of k is shown by the solid line in Fig. 2. When collisions are rare (mean free path longer than the distance between the transmitter and the receiver) the experimental points agree with this one-dimensional and collisionless-case theoretical curve. The damping rates also agree with the theoretical values from the Vlasov model. This shows that the wave excited in the low-pressure regime is a well-defined one-dimensional electrostatic electron wave.[1]

As the collision frequency increases and the mean free path becomes shorter than the propagation distance, it is found experimentally that both the real and imaginary parts of the dispersion relation are altered. The change in the imaginary part of the wave number shows the enhancement of the damping rate. This is particularly strong when the frequency of the wave is close to the plasma frequency. The reason why the damping rate k_i becomes large at $\omega \approx \omega_p$ is explained by the fact that the group velocity of the wave v_g becomes very small so that $\nu/v_g = k_{ic}$ becomes large. We assume the experimental

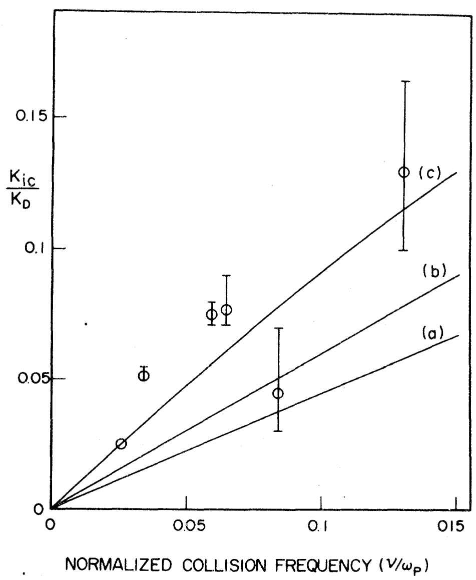

FIG. 3. Effect of the collision on the imaginary part of the wave number. Here the wave frequency is fixed: $\omega/\omega_p = 1.3$. The solid lines correspond to the models (a), (b), and (c), respectively.

damping rate of the wave (k_i) is given by

$$k_i = k_{ic} + k_{iL},$$

where k_{ic} and k_{iL} are those due to collisional and Landau damping, respectively. We plotted k_{ic} in Fig. 3 as a function of ν/ω_p for $\omega/\omega_{pe} \approx 1.3$. From both Figs. 1 and 2 we see that there is an appreciable increase of the wave number with increasing collision frequency.

It is quite difficult to solve the detailed kinetic equations for the collision regimes involved here. We have tried to explain these results theoretically by using three different fluid models:

(a) An electron fluid model obeying an adiabatic law with $\gamma = 3$ (one degree of freedom involved) and with momentum transfer due to electron neutral collisions.

(b) An electron fluid model with $\gamma = \frac{5}{3}$ (complete isotropization of the electron distribution function) and momentum transfer due to electron neutral collisions.

(c) An electron fluid model with different temperatures parallel and perpendicular to $\boldsymbol{k}$ with temperature relaxation and momentum transfer due to electron neutral collisions.

The dispersion relations for the three models are, respectively,

$$\omega(\omega - i\nu) = \omega_p^2 + 3|k_r + ik_i|^2 v_e^2, \tag{2a}$$

$$\omega(\omega - i\nu) = \omega_p^2 + \tfrac{5}{3}|k_r + ik_i|^2 v_e^2, \tag{2b}$$

$$\frac{\omega^2}{\omega_p^2} - 1 = \frac{k^2}{k_d^2}\left[1 + 2\left(1 - \frac{4i}{\omega\tau} + \frac{8}{\omega\tau(\omega\tau - 2i)}\right)^{-1}\right] + i\frac{\omega^2}{\omega\tau}\frac{1}{\omega_p^2}, \tag{2c}$$

where τ is the collisional time ($\tau = 1/\nu$). This gives the ordinary dispersion relations in two extreme cases; (i) $\omega^2 = \omega_p^2 + 3k^2 v_e^2$ (for $\tau \to \infty$), and (ii) $\omega^2 = \omega_p^2 + \frac{5}{3}k^2 v_e^2$ (for $\tau \to 0$ and with the last term the momentum-transfer term dropped). The effect of the collisions appears through the change of the adiabatic compression from one-dimensional to three-dimensional as well as through the momentum transfer.

By comparing the experimental points with the theoretical curves in Fig. 3, we see that curve (c) agrees best with the experiments. Thus one can expect a change of γ with the collision frequency. Associated with the change in γ is an enhanced damping and a shift in the real part of the wave number.[6]

For the real part of the wave number, the experimental points are difficult to understand if we compare these results with the theoretical results of Bogdanov and Willett,[7] for according to their theory the real part of the wave number does not change so much when $\nu/\omega_{pe} \lesssim 0.5$. Equation (2c) shows that as ν increases the real part of k, k_r/k_D, increases and also we have propagation at frequencies lower than ω_p.

Thus, the characteristics of Eq. (2c) explain the experimental results qualitatively. Quantitatively, we cannot expect perfect agreement because the experiments overlap the collisionless regime with $k/k_D \sim 1$, where the fluid model is not valid; this regime is well described by the Vlasov model. If we compare the data on k_r with the results of Eq. (2c) quantitatively, then the "effective" collision frequency ν_{eff} for electrons with neutrals appears to be larger than would be calculated from available cross sections. The ratio $\nu_{eff}/\nu = r$ is about $3 \sim 8$, if we compare the real part of the wave number from the experiments with the results of the theory. The origin of the "enhanced" collisions is not understood now, but the following model[8] has been proposed. The wave is formed by a number of electrons in the plasma, and most of them have a slower velocity than the thermal velocity. These slow electrons suffer scattering by the neutral atoms or low-frequency noises in the plasma, produced by the discharge in the plasma sources. If the low-frequency noise becomes large when we increase the gas pressure, this may explain the enhancement of the collisions. In usual dc discharge experiments in an inert gas in this pressure regime ($10^{-3} \sim 10^{-5}$ Torr), it has been known that low-frequency noise (around ω_{pi}) appears in a limited pressure range. One problem remains: Choosing ν_{eff} to give the correct real part of k will give too large a value for k_i. Thus though model (c) appears to be the most satisfactory, it does not completely explain the observations.

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*Permanent address: Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

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Direct Optical Coupling to Surface Excitations

A. S. Barker, Jr.
Bell Telephone Laboratories, Murray Hill, New Jersey 07974
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A method is described of directly coupling an optical beam to surface excitations. Using this technique the frequency and linewidth of surface plasmons in doped germanium and in gold and surface phonons in calcium molybdate are determined. The method also allows the dispersion curve to be measured.

Surface plasmons are wave-type excitations which can exist at the surface of a metal or doped semiconductor.[1,2] These excitations were first detected by electron scattering from thin metal foils.[3] Similar surface phonon excitations have been detected by slow-electron reflection spectroscopy.[4] Recently an indirect optical beam interaction has been reported for the case where the surface is roughened either in a random manner[5] or by ruling a grating.[6] Theoretical attempts to fit such optical experiments are considerably hampered by the complications introduced by the roughness itself.[7] The present paper shows a very direct method of coupling to surface modes of plasmon, phonon, exciton, or mixed character. The surface remains undisturbed and the method allows the coupling to be calculated exactly.

A surface plasmon or surface phonon wave is characterized by an electric field which oscillates in time and varies sinusoidally in directions along the surface but falls off exponentially in the directions perpendicular to the surface. Figure 1 shows the spatial pattern of the electric field. In the figure, k is the wave vector along the surface. The actual form of the electric field for large k is

$$\vec{E} = E_0(\hat{x} + i\hat{z})e^{i(kx-\omega t)}e^{-k|z|}, \quad (1)$$

where $\hat{x}$ and $\hat{z}$ are unit vectors as shown in the Fig. 1(a). The dispersion curve for surface plasmons is illustrated in Fig. 1(b).[8] For k large compared to ω/c but still very much smaller than k_F,[9] the dispersion curve becomes horizontal and is asymptotic to the frequency determined by

$$\mathrm{Re}[\epsilon(\omega)] = -1. \quad (2)$$

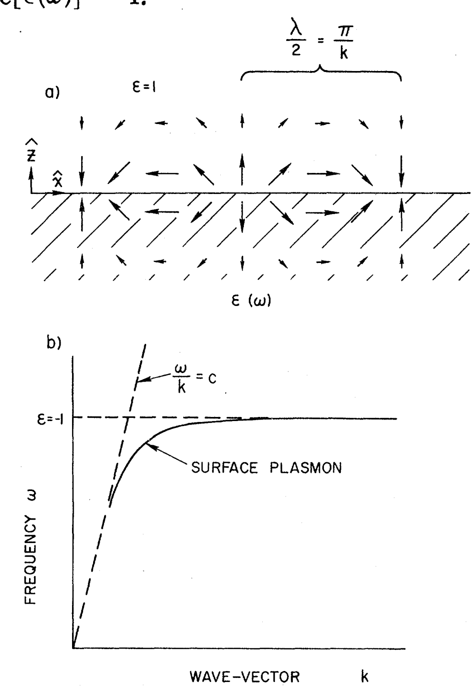

FIG. 1. (a) Spatial dependence of the electric vector for a surface plasmon or phonon. The wave propagates along the x direction and has maximum amplitude at the interface between the two media. (b) Surface plasmon dispersion curve for an air-metal interface. For an air-dielectric interface, the small-k part of the curve can drop only as far as the frequency where ϵ has its pole.