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14. Abstract/Notes

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# LARGE AMPLITUDE SOLITARY WAVES IN A MULTICOMPONENT PLASMA WITH NEGATIVE IONS

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When the concentration of negative ions is larger than a critical value, a small compressive pulse evolves into a subsonic wave train and a large pulse develops into a solitary wave. The threshold amplitude and velocity of the solitary waves are measured and compared with predictions using the pseudopotential method.

Ion-acoustic solitons have been investigated experimentally in detail and are reviewed in several papers [1]. The solitons, being a compression of plasma density, have a positive potential perturbation in a plasma. If negative ions are present, a rarefactive or negative potential soliton may exist in the plasma. Rarefactive solitons have been observed in a multicomponent plasma with negative ions when the negative ion concentration $r$ is larger than a critical value $r_c$ [2]. These compressive ($r < r_c$) and rarefactive ($r > r_c$) solitons can be described by the Korteweg–de Vries (KdV) equation. In a recent experiment [3], both compressive and rarefactive solitons which are predicted by the modified KdV equation are observed when $r = r_c$ and their properties are described. The amplitude of the KdV and modified KdV solitons must be theoretically smaller, i.e., $|\delta n/n| \ll 1$, where $\delta n$ and $n$ are the perturbed and unperturbed electron density [4,5], and the experimentally measured amplitude ($|\delta n/n| < 0.3$) was also small [1]. If the amplitude were large, the perturbation method used to derive the two equations cannot be applied and the original fluid equations must be considered. However, when a wave shape is *temporarily stationary*, the *pseudo or Sagdeev potential method* [6] predicts that there exist localized perturbations with a large amplitude [7]. The purpose of this paper is to report what we believe to be the first observation of such a large amplitude ion-acoustic solitary wave which can be predicted by the pseudopotential method.

We consider a three-component plasma of positive and negative ions and Boltzmann electrons. We assume the temperatures satisfy $T_e \gg T_i \approx 0$. From the equations of motion, equations of continuity for both positive and negative ions and Poisson's equation, the following relation is obtained for stationary perturbations:

$$d^2\psi/dx^2 = -\, dV/d\psi ,$$

$$V = 1 - e^{\psi} + \frac{M^2S^2}{1-r}\left[1 - (1 - 2\psi/M^2S^2)^{1/2}\right] + \frac{\mu r M^2 S^2}{1-r}\left[1 - (1 + 2\psi/\mu M^2 S^2)^{1/2}\right] , \quad (1)$$

where $\psi = e\phi/\kappa T_e$, $\phi$ is the wave potential, $x$ is the distance normalized by the electron Debye length ($= (\kappa T_e/4\pi n e^2)^{1/2}$), and $V$ is the pseudo or Sagdeev potential. Furthermore, $\mu = M_-/M_+$, where $M_-$ and $M_+$ are the masses of the negative and positive ions; $r = n_-/n_+$, where $n_-$ and $n_+$ are the unperturbed densities of negative and positive ions; $M$ is the Mach number, i.e., the velocity normalized by the ion-acoustic velocity $C_s$; and $S$ is $C_s$ normalized by $(\kappa T_e/M_+)^{1/2}$, and is

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given by

$$S = \left(\frac{1 + r/\mu}{1 - r}\right)^{1/2} . \quad (2)$$

Here, charge neutrality, $n_+ = n_- + n$, is assumed.

The regions of $\psi$ and $r$ for the existence of solitary wave solutions are shown in fig. 1. The pseudopotentials $V$ versus $\phi$ in various regions are also drawn in the figure. When $r = 0$, which corresponds to no negative ions, only compressive solitons ($\phi > 0$) exist although their amplitude is limited to $\psi = 1.25$ whose Mach number (= 1.6) is well known as the critical Mach number. When $0.017 < r \leq r_c = 0.10$, negative solitons can exist if $\psi$ is within certain values. When $r \geq 0.10$ and $|\psi| \ll 1$, only rarefactive solitons can propagate. However, when $0.10 < r < 0.494$, compressive solitary waves of large amplitude can be excited. Both positive and negative solitons whose $|\psi| \ll 1$ when $r \approx 0.1$ are described by the modified KdV equation [3,5]. Characteristics of negative solitons of small amplitude when $r > 0.1$ are predicted by the KdV equation [2].

An experiment to observe the properties of these solitary waves has been carried out in a multidipole double-plasma machine [3]. The inner (plasma) diameter of the device is 40 cm and its total length is 90 cm. The device is separated into a driver and a target section with a floating grid. The grid consists of a mesh 20 lines/in. with a transparency of 85%. The cathodes are 0.1 mm diam. tungsten filaments placed 6 cm from the surface of the anode wall. Each section has fifteen filaments with a length of 5 cm. The chamber was evacuated to $1 \times 10^{-6}$ Torr with a turbomolecular pump. Argon and sulfur hexafluoride were introduced independently into the chamber under continuous pumping. The pressure of Ar was about $1.5 \times 10^{-4}$ Torr and the partial pressure of $SF_6$ was changed from 0 to $2 \times 10^{-5}$ Torr. The discharge voltage and current were 50 V and 50–100 mA. Plasma parameters as measured with a small Langmuir probe and a retarding-ion energy analyzer were $n = 10^8 - 10^9$ cm$^{-3}$, $T_e \approx 1.5$ eV, and $T_e/T_i \approx 20$. Ion-acoustic perturbations were excited by either a positive or a negative sinusoidal voltage pulse applied to the anode of the driver plasma. Signals were detected by the axially movable probe biased positive with respect to the plasma potential in order to detect perturbations in the electron saturation current.

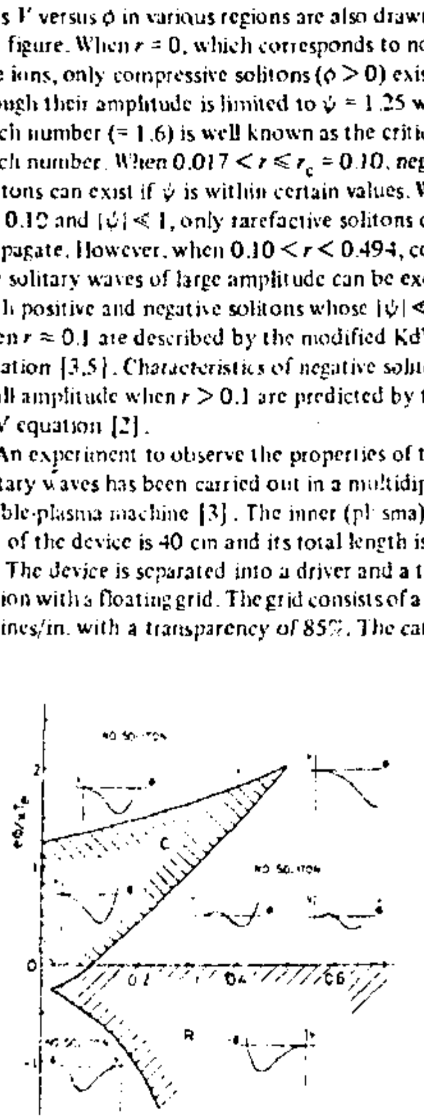


Fig. 1. Regions of compressive or positive solitary waves (C) and rarefactive or negative solitary waves (R). $\mu = 0.476$.

In the present discharge conditions, the plasma included several species of positive and negative ions such as $Ar^+$, $SF_5^+$, $F^-$ and $SF_6^-$. However, since ions with a lighter mass dominate the ion-acoustic wave, the plasma may be considered to be composed of $Ar^+$, $F^-$, and electrons. This has been confirmed in the previous experiment [2]. As a result of this, the mass ratio $\mu = 0.476$. The experimental $r = n_{F^-}/n_{Ar^+}$ is estimated from eq. (2) by use of the measured $T_e$ with the probe and $C_s$ obtained from interferometer patterns of small amplitude continuous ion-acoustic waves of low frequencies (< 200 kHz).

Signals detected at 4.3 cm from the grid for different excitation voltages when $r = 0.25$ are shown in fig. 2. When the negative pulse is applied (– 1.5 V), rarefactive solitons are formed since the wave is described by the KdV equation whose coefficient of the nonlinear term is negative [2]. When a 1.5 V positive pulse is applied and when its amplitude is small, i.e., $\delta n/n \approx 0.25$, the leading part of the pulse becomes gentle, which implies that the velocity of the peak of the positive pulse is less than the ion-acoustic velocity $C_s$. The falling part steepens to form oscillations due to dispersion. The oscillations become wider and wider as the wave propagates so that no solitary pulse is formed. This is similar to the propagation of a negative pulse in a plasma without negative ions [8]. When the amplitude is increased (4 and 5 V) to reach a critical value ($\delta n/n = 0.76$), the leading part of the pulse whose ini-

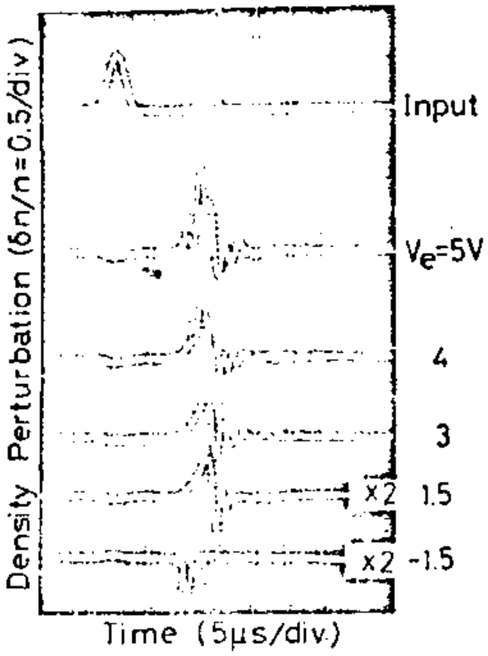


Fig. 2. Observed perturbations of the electron density at 4.3 cm from the grid for different peak amplitude voltages. $r = 0.25 > r_c$.

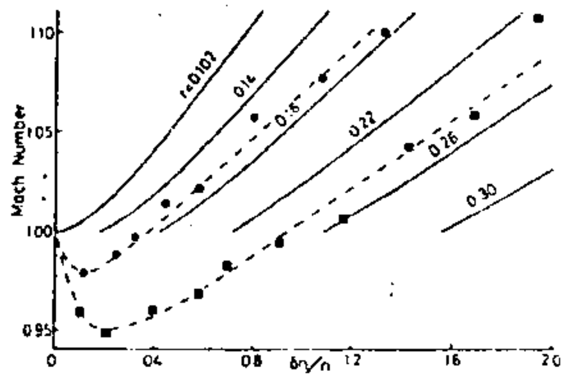


Fig. 3. The dependence of the peak velocity on the peak height. Closed circles: $r = 0.17$. Closed squares: $r = 0.28$. The solid curves are calculated from eq. (1) for $\mu = 0.476$.

tial shape is similar to the top trace in fig. 2 steepens to form a solitary peak due to dispersion. It is noted that the amplitude ($\delta n/n \approx 1.2$) is very large and we believe this is the largest solitary wave ever observed in plasmas. The small peak in front of the solitary wave (5 V) is a burst of positive ions consisting of both reflected ions and ions involved in the DP excitation [9]. The present efficient excitation is due to the presence of the negative ions, whose mechanism is under investigation.

Examples of the measured velocity of the peak as a function of the peak height are shown in fig. 3. When the amplitude is increased from a small linear pulse, the velocity of the peak decreases due to the negative nonlinearity described above. After reaching a minimum, the velocity increases and becomes supersonic at a certain amplitude. This threshold amplitude is nearly equal to the one at which the steepening occurs at the leading part as noted in fig. 2. Eq. (1) predicts that the solitary waves are supersonic and the amplitude when $M = 1$ gives the threshold amplitude shown in fig. 1. The experimental results for $M > 1$ are considered to agree with the theory.

The spatial width of the solitary peak, which becomes narrower when its amplitude is larger, is also measured. The result agrees with that of the theoretical localized peak obtained numerically from eq. (1).

Measured threshold amplitudes at which the wave becomes supersonic or the steepening occurs at the leading part of the pulse are plotted in fig. 4 as a function of $r$. The amplitudes were also measured with the Langmuir probe characteristics taken at the solitons

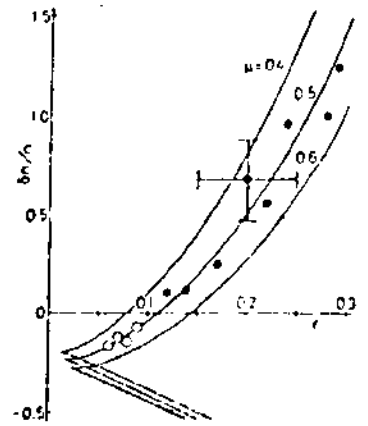


Fig. 4. The dependence of critical amplitudes on $r$. The open and closed circles are rarefactive and compressive waves, respectively. The curves are calculated from eq. (1).

by a sampling technique. Electrons in the solitary wave have almost Boltzmann distribution, which will be described elsewhere. The vertical axis in fig. 4 is not $\psi$ but $\delta n/n$ whose theoretical value is obtained from the relation $\delta n/n = e^{\psi} - 1$ using the critical $\psi$ shown in fig. 1. Measured critical depths for the formation of rarefactive solitary peaks when $r < r_c$ are also plotted in the same figure. Experimental results seem to agree with the theory and a disagreement is thought to be due to neglecting the finite ion temperature and the other species of positive and negative ions and due to the assumption of Boltzmann electrons.

In summary, the observation and study of large amplitude solitary waves ($e\phi \approx \kappa T_e$) in plasmas with negative ions have been presented. The wave cannot be described with the KdV or the modified KdV equations, however, the pseudopotential method gives a quantitative account of these solitary waves.

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