Observation of Ion-Acoustic Rarefaction Solitons in a Multicomponent Plasma with Negative Ions

G. O. Ludwig and J. L. Ferreira
Instituto de Pesquisas Espaciais, Conselho Nacional de Desenvolvimento Científico e Tecnológico, 12200 São José dos Campos, São Paulo, Brazil

and

Y. Nakamura
Institute of Space and Astronautical Science, Komaba, Meguro-ku, Tokyo, Japan
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The propagation of ion-acoustic solitons in a plasma with negative ions has been observed. For sufficiently large concentration of negative ions, applied rarefactive (negative) voltage pulses break up into solitons, whereas compressive pulses evolve into wave trains, with exactly the opposite behavior as that for a plasma composed only of positive ions. There is a critical value of the negative-ion concentration for which a finite-amplitude pulse propagates without steepening.

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It is well known from the nonlinear fluid theory of ion-acoustic waves, in a plasma consisting of positive ions, that an initial compressive perturbation breaks up into a number of solitons, whereas a rarefactive perturbation generates a subsonic wave train.[1,2] Theoretically, it has been shown, from the solution of the Korteweg-de Vries (KdV) equation, that rarefaction solitons can be excited in multicomponent plasmas with negative ions.[3] The rarefaction soliton, which corresponds to a depression in the plasma potential, is actually related to a compression of the negative ions, in such a way that the steepening in the leading edge of the propagating pulse is balanced by the negative dispersive effect in the ion-acoustic regime.

This Letter reports the experimental observation of rarefaction solitons in plasmas produced by a filament-anode 50-V dc discharge in a mixture of argon and sulfur hexafluoride. The experiment was performed in the Institute for Space Research (INPE) double-plasma (DP) machine. This DP device is 30 cm in diameter and its total length is 75 cm. The plasma is surface confined by a multidipole magnetic field and the discharge current is approximately 200 mA. Typical operating parameters in argon at a pressure of about 3×10^{-4} mbar are $n_e \cong 1.3\times10^9$ cm^{-3}, $T_e \cong 2.3$ eV (Langmuir-probe data), and $T_i \cong 0.3$ eV. The dc potential difference between the two plasmas was adjusted so that no ion beam was present, as confirmed by electrostatic ion-energy-analyzer measurements. Compressive and rarefactive pulses were launched in the target plasma by the application of voltage pulses to the driver plasma.

A plasma with negative ions can be easily produced by the introduction of a gas with a large electron-attachment cross section, such as SF_6, into the discharge chamber.[4] Bombardment of SF_6 molecules by the 50-eV primary electrons leads mainly to the formation of negative F^- ions as a result of dissociative attachment processes.[5,6] Negative SF_6^- and SF_5^- ions are also formed by the capture of very-low-energy plasma electrons, a simple calculation showing that for an electron temperature of 2.3 eV the production rate of SF_5^- ions is much larger than that of SF_6^-. Furthermore, the ionization of SF_6 by the primary electrons leads to the formation of SF_5^+, SF_3^+, SF_4^+, etc., where SF_5^+ is the most abundant species according to mass-spectrometric studies.[7] These considerations lead us to conclude that the plasma produced is essentially a four-ion-species plasma, composed of positive Ar^+ ions, positive SF_5^+ ions, negative F^- ions, negative (SF_5^-) ions, and electrons.

The production rate of F^- divided by the production rate of SF_5^- is proportional to the ratio between the primary, n_0, and plasma, n_e, electron densities. Therefore, for a constant discharge current, the concentration of F^- ions is much smaller than that of SF_5^- ions when the partial pressure of SF_6 in the discharge chamber is low ($n_0/n_e \ll 1$). If we introduce a larger fraction of SF_6 gas, the total negative-ion concentration increases (n_e decreases), the density of F^- ions relative to SF_5^- ions increases, and the lighter ions rapidly dominate the propagation characteristics of ion-acoustic waves. This simplified description of the plasma is justified by the good agreement between experimental and theoretical values for the ion-acoustic speed, as a function of the ion concentrations, as shown in Fig. 1. The ion-acoustic speed for the fast mode[8,9] in a four-cold-ion-species plasma composed of $Ar^+ + SF_5^+ + F^- + SF_5^-$, normalized to the ion-acoustic speed for a pure cold argon plasma, is given by

$$\hat{C}_s = \frac{C_s}{(k_B T_e/m_{Ar})^{1/2}} = \left(\frac{1-(1-1/\mu_+)\rho_+ + [(1-\rho_-)/\mu_- + \rho_-/\mu_-']r}{1-r}\right)^{1/2}, \qquad (1)$$

where $r = (n_{F^-} + n_{SF_5^-})/(n_{Ar^+} + n_{SF_5^+})$, $\rho_+ = n_{SF_5^+}/(n_{Ar^+} + n_{SF_5^+})$, and $\rho_- = n_{SF_5^-}/(n_{F^-} + n_{SF_5^-})$. The mass ratios are $\mu_- = m_{F^-}/m_{Ar^+} = 0.476$, $\mu_+ = m_{SF_5^+}/m_{Ar^+} = 3.18$, and $\mu_-' = m_{SF_5^-}/m_{Ar^+} = \mu_+$. Experimentally, the negative-ion concentration, r, was determined from the relative changes in the electron and ion saturation currents. It can be shown that

$$r \cong 1 - \frac{I_{es}}{I_{es}^{(0)}}\frac{I_{is}^{(0)}}{I_{is}}\left[1-\left(1-\frac{1}{\mu_+^{1/2}}\right)\rho_+\right],$$

where I and $I^{(0)}$ are the saturation currents with and without SF_6, for constant partial pressures of argon (there is no appreciable change in the electron temperature). The ratio between the density of contaminating SF_5^+ ions and the total density of positive ions is given by

$$\rho_+ \cong \alpha\mu_+^{1/2}(P_{SF_6}/P_{Ar})(1+\alpha\mu_+^{1/2}P_{SF_6}/P_{Ar})^{-1},$$

where P refers to the ion-gauge readings of the partial pressures for each gas and α is the pressure-reading correction factor which, for a 50-V filament-anode discharge potential and a 200-V potential at the grid of the Bayard-Alpert gauge, becomes[10]

$$\alpha = \frac{(\sigma_{SF_5^+}/\sigma_{Ar^+})_{50\text{ eV}}}{(\sigma_{SF_5^+}/\sigma_{Ar^+})_{200\text{ eV}}} = 0.601.$$

The ratio ρ_- between the density of contaminating SF_5^- ions and the total density of negative ions was estimated to vary between 0.95 and 0.65 for the lowest and the highest values, respectively, of the partial pressure of SF_6 used in the experiment. Nevertheless, the experimental results clearly indicate that the effect of SF_5^- ions on the propagation of ion-acoustic waves is much smaller than that of the lighter F^- ions. The agreement between the theoretical and experimental values in Fig. 1 will be even better if one takes into account finite-ion-temperature effects. Figure 2 shows the formation and propagation of a rarefaction soliton excited by a pulsed negative potential difference applied between the plasmas. This figure clearly shows the steepening of the wave front and the development of an oscillatory structure (the time-stationary hump is a direct coupled signal). The amplitude, width, and velocity dependence of the leading peak, at large distances from the separating grid, were determined for a variety of experimental conditions and are

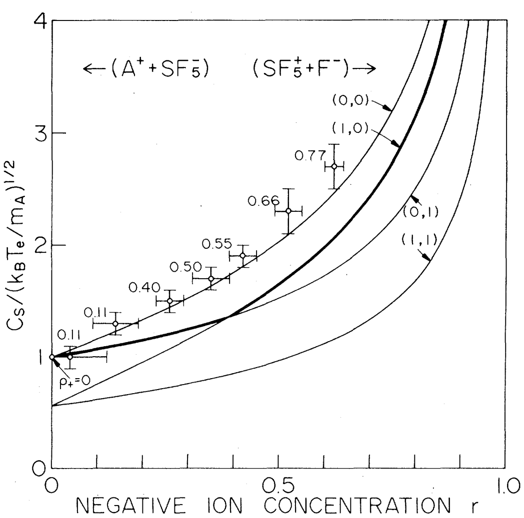

FIG. 1. Normalized ion-acoustic speed of the fast ion mode in a plasma with negative ions. Solid lines indicate Eq. (1), with heavy lines corresponding to asymptotic behavior. Curve numbering indicates the pair of values (ρ_+, ρ_-). Point numbering indicates the measured values of ρ_+.

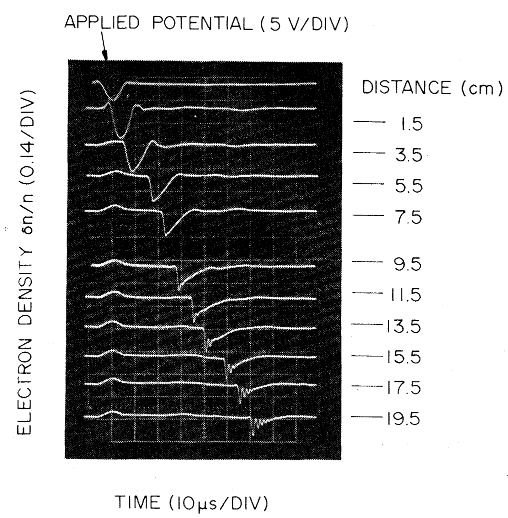

FIG. 2. Electron density vs time, with distance as parameter, for $r \cong 0.24$ and $\rho_+ \cong 0.38$. The Mach number is $M \cong 1.09$.

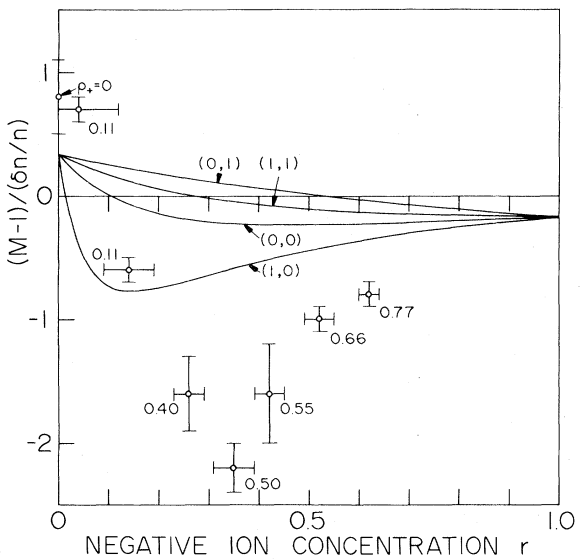

FIG. 3. Experimental and theoretical results for the ratio $(M-1)/(\delta n/n)$ as a function of r. Solid lines indicate Eq. (2). Numbering is as in Fig. 1.

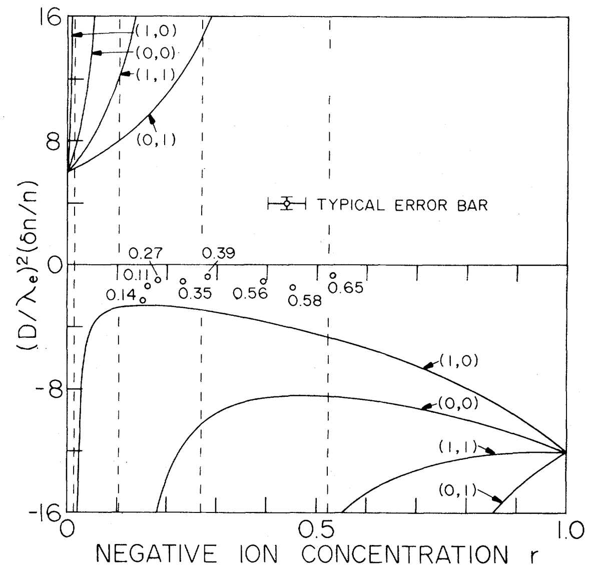

FIG. 4. Experimental and theoretical results for the product $(D/\lambda_e)^2(\delta n/n)$ as a function of r. Solid lines indicate Eq. (3). Numbering is as in Fig. 1.

consistent with the general properties of a soliton given by Eqs. (2) and (3) below. The second peak roughly satisfies these requirements but the results are not yet conclusive.

Plots of velocity versus amplitude allow the determination of the experimental ratio $(M-1)/(\delta n/n)$, where M is the Mach number, as shown in Fig. 3. Below a certain critical value of $r \sim 0.1$ compression solitons are excited in the $(Ar^+ + SF_5^+ + F^- + SF_5^-)$ plasma, whereas above this critical value only rarefaction solitons can propagate. This property of a plasma with negative ions is correctly described by the KdV equation for weakly nonlinear ion sound waves[11]:

$$\frac{\partial \hat{\varphi}^{(1)}}{\partial \tau} + \frac{A}{B}\hat{\varphi}^{(1)}\frac{\partial \hat{\varphi}^{(1)}}{\partial \xi} + \frac{1}{2B}\frac{\partial^3 \hat{\varphi}^{(1)}}{\partial \xi^3} = 0,$$

where

$$A = \frac{3}{2}\frac{\{1-(1-1/\mu_+^2)\rho_+ - [(1-\rho_-)/\mu_-^2 + \rho_-/\mu_-'^2]r\}(1-r)}{\{1-(1-1/\mu_+)\rho_+ + [(1-\rho_-)/\mu_- + \rho_-/\mu_-']r\}^2} - \frac{1}{2},$$

and $B = 1/\hat{C}_s$ in the cold-ion limit. There is a critical concentration of negative ions, equal to 0.102 for an $(Ar^+ + F^-)$ plasma, for which $A=0$. When r is close to this critical value the nonlinear term in the KdV equation vanishes; the delicate balance between nonlinearity and dispersion, necessary to the production of a soliton, is broken and it becomes impossible to excite a soliton. In this case, a finite-amplitude pulse can propagate without steepening, an interesting result confirmed by our experiment. For concentrations greater than critical the coefficient A becomes negative. For soliton solutions, the dimensionless electric potential, $\hat{\varphi} = e\varphi/k_B T_e$, must also be negative. Hence, the KdV equation predicts correctly the existence of rarefaction solitons in a plasma with a sufficiently large fraction of negative ions. However, the theoretical values for the soliton Mach number and width are quite different from those obtained experimentally. This is illustrated in Figs. 3 and 4, where the theoretical and experimental values of $(M-1)/(\delta n/n)$ and $(D/\lambda_e)^2(\delta n/n)$ are compared (D/λ_e is the soliton width normalized to the electron Debye length). The theoretically predicted values are

$$M = 1 + (A/3B\hat{C}_s)(\delta n/n), \tag{2}$$

$$D/\lambda_e = [(6/A)/(\delta n/n)]^{1/2}. \tag{3}$$

As can be seen, the observed values of M are quite larger (and the observed values of D smaller) than predicted by the solution of the KdV equation derived from the simple fluid model with cold ions and isothermal electrons. The inclusion of finite-ion-temperature effects does not improve matters in this respect. In order to remove the discrepancy between theory and experiment kinetic effects, such as negative ions and electrons reflected by the negative potential well plus trapped positive ions, have to be included in the theoretical model. Fluid models such as the simple KdV equation do not give a satisfactory fit to experimental data for solitons in a multi-ion plasma.[1] It must be pointed out that, with use of the pseudopotential approach[12] in the analysis of time-independent solutions, the fluid model predicts the existence of solitons with very large Mach numbers. Indeed, the maximum Mach number for rarefaction solitons has no upper limit when the concentration of negative ions exceeds a critical value, smaller than 0.5. Furthermore, the pseudopotential approach predicts a range of values of r and M for which compression and rarefaction solitons exist simultaneously. This aspect was, at least qualitatively, confirmed by experiment.

In summary, the observation and systematic study of fast ion-acoustic rarefaction solitons in plasmas with negative ions has been presented. The simple KdV equation gives a qualitative account of these rarefaction solitons, but the quantitative comparison requires the inclusion of kinetic effects in the theoretical model. A more complete description of the pertinent theoretical and experimental work will be reported elsewhere.

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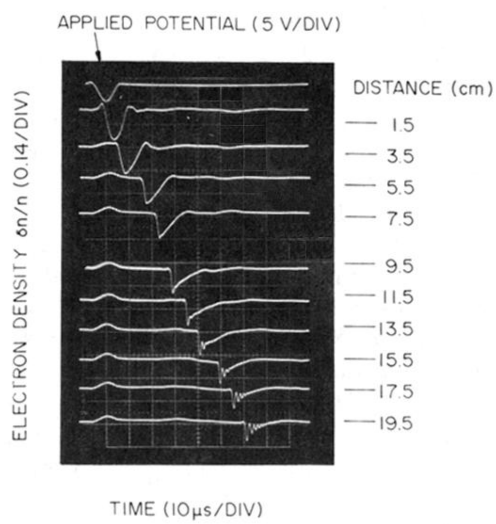

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