LETTERS

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Double layers in a plasma with negative ions

Robert L. Merlino and Jackson J. Loomis
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

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The formation of strong double layers in a plasma consisting of positive ions, negative ions, and electrons has been investigated in a triple-plasma device. When a strong double layer is present in a positive ion/electron plasma, the introduction of negative ions results in the formation of a second double layer which is separated from the first double layer by a region of quasineutral plasma.

There is considerable current interest in understanding the behavior of plasmas containing positive ions, electrons, and significant concentrations of negative ions. High-pressure electrical discharges in electronegative gases have been studied for some time.[1] Negative ion plasmas are found in the D region of the ionosphere,[2] plasma processing reactors,[3] and neutral beam sources.[4] They have been studied in high-current-density diffuse discharges which are used to pump high-power gaseous lasers,[5] and in constricted discharges appearing in high-current switchgear.[6] In addition, highly reactive, electron attaching gases have been released into the upper atmosphere to artificially induce "ionospheric holes."[7] Studies of negative ion plasmas may also be applied in attempting to understand the properties of "dusty plasmas," which contain massive, negatively charged particles.[8] Laboratory experiments in plasmas containing negative ions have investigated solitons,[9] ion acoustic waves,[10,11] electrostatic ion cyclotron waves,[12] beam–plasma interactions,[13] and turbulence.[14] A useful summary of negative ion plasma sources has recently been presented by Sheehan and Rynn.[15] A method for producing plasmas with nearly all electrons replaced by negative ions has been described by Wong *et al.*[10] and Hershkowitz and Intrator.[16]

In this Letter we report on an experimental study of strong double layer formation in a plasma composed of positive ions, negative ions, and electrons. Strong double layers are regions of localized electrostatic field in a plasma, with a potential drop, considerably larger than kT_e/e, extending over distances typically of the order of several Debye lengths to several hundred Debye lengths. (A review of recent laboratory work on double layers has been given by Hershkowitz.[17]) In a triple-plasma device, a strong double layer is formed at the boundary between two independently produced plasmas with different space potentials. Under certain conditions described below, the introduction of negative ions into the plasma results in the formation of *two* double layers which are separated by a region of quasineutral plasma. The formation of multiple double layers in positive ion–electron plasmas has also been reported.[18,19]

The experiments were performed in the triple-plasma device shown schematically in Fig. 1. Plasmas are produced in the two aluminum source chambers, S1 and S2, by hot-filament discharges in argon, typically at neutral pressures $\sim 10^{-4}$ T, and discharge voltages $V_1 = V_2 = 80$ V. Axial magnetic field coils are available but were not used in this experiment. Typical source densities and electron temperatures are $n_e \sim 10^9$–10^{10} cm^{-3} and $T_e \sim 2$–4 eV. The source plasmas flow into the central grounded chamber through 10 cm diameter apertures A1 and A2 which are also grounded. Chamber S2 is electrically isolated from the rest of the system so that its anode potential can be controlled by adjusting V_{12}. The plasma potential in S2 is usually a few volts above V_{12}, whereas the potential of S1 is usually a few volts above ground. When both sources are grounded, i.e., $V_{12} = 0$, the potential in the central region is approximately uniform and within a few volts of ground. The plasma density drops as the plasmas flow through A1 and A2, and then rises slightly, resulting in a broad density maximum near the center of the chamber. The peak density on axis, under these conditions, is usually an order of magnitude below the source densities.

Plasmas containing appreciable concentrations of negative ions were produced by admitting SF_6 gas into the sys-

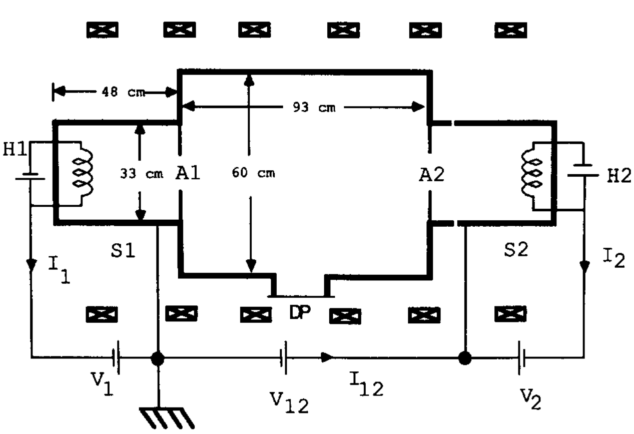

FIG. 1. Schematic diagram of the triple-plasma device. A plasma is maintained in the central region by the inflow of plasma through A1 and A2 from the sources S1 and S2. Double layers are produced in the central region by applying the bias V_{12} between S1 and S2.

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tem; SF_6 is a highly electronegative molecule with a large electron attachment cross section.[20] Low-energy (0.2 eV) electrons attach to the SF_6 molecules forming the SF_6^- negative ion, although in discharge plasmas other reactions are also possible leading to the formation of SF_5^- and F^-.[9,20] Ionization of SF_6 by the energetic primary electrons may also occur, resulting mainly in the formation of SF_5^+ positive ions.[20] The attachment of electrons to form the heavy negative ions is observed as a reduction in the electron saturation current to a Langmuir probe since, even for relatively high negative ion concentrations, this current is due primarily to the more mobile electrons. For example, when the SF_6 partial pressure is increased from zero up to about 25%, the electron saturation current decreases by about an order of magnitude, indicating a negative ion concentration, $n_-/n_+ \sim 90\%$, where $n_{-/+}$ is the negative/positive ion density. The discharges with negative ions tend to be very noisy so that precise measurements of the negative ion concentrations using Langmuir probes are difficult to obtain.

A typical example of a double layer formed in an Ar^+ electron plasma when the S2 bias, V_{12}, is raised to 45 V, is shown in Fig. 2(a). These data were obtained from measurements of the floating potential of an emissive probe at various axial positions. For this case the argon pressure was 1.5×10^{-4} T, the source discharge currents $I_1 = I_2 = 1$ A, and $I_{12} = 0.2$ A. The double layer potential drop, V_{DL}, is such that $V_{DL}/kT_e \sim 10$. The two-dimensional double layer equipotential contours are shown in Fig. 2(b), measured in the midplane of the device. If the applied potential V_{12} is increased, V_{DL} does not increase further, but there is an overall increase in potential throughout the device, with the remaining axial potential drop occurring in a sheath near the filaments in S1. The axial position of the double layer in a triple-plasma device can be varied by changing the source densities.[21]

The effect of introducing SF_6 at a partial pressure of 4×10^{-5} T, under the conditions just described (Fig. 2), is shown in Fig. 3(a). At this SF_6 partial pressure, Langmuir probe measurements in S1 indicate a negative ion concentration n_-/n_+ in the range 0.8–0.9. The negative ions have the effect of lowering the potential, by more than 10 V, up to about 60 cm from A1, where a second double layer is formed. The full two-dimensional potential contours for this case are shown in Fig. 3(b). The locations of the two double layers can be varied by changing the source discharge currents, the source bias V_{12}, or the pressures. We made some checks to confirm that the formation of *two* double layers was due to the presence of the negative ions and not a result of the production of any additional positive ion species from the ionization of SF_6. We could not produce two double layers in plasmas consisting of electrons, and combinations of either Ar^+ and He^+ or Ar^+ and Xe^+, or in Ar^+/electron plasmas simply by increasing or decreasing the argon pressure.

The observation of two double layers in the negative ion

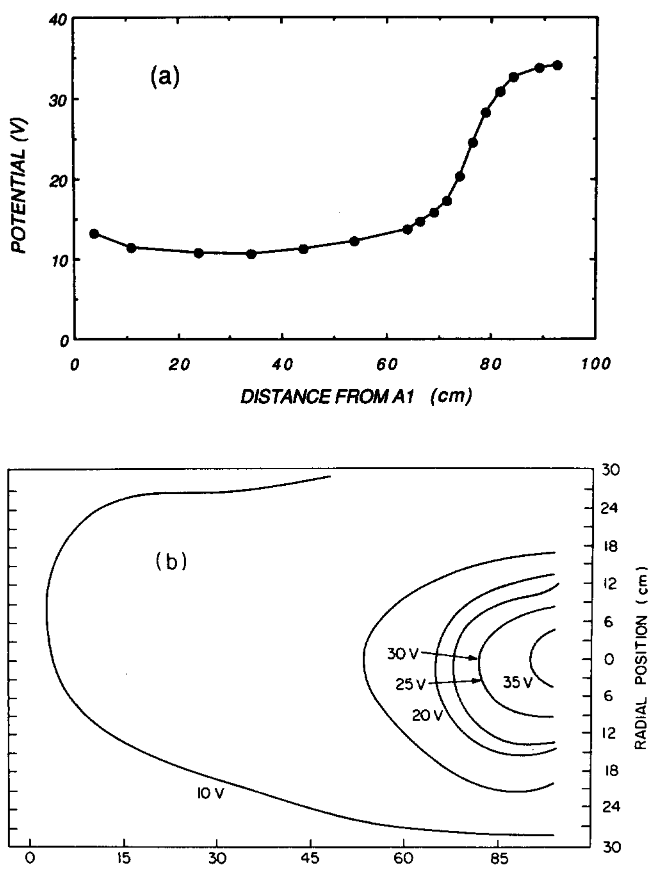

FIG. 2. Double layer produced in an Ar^+/electron plasma, for $P(\mathrm{Ar}) = 1.5\times10^{-4}$ T and $V_{12} = 45$ V. (a) Axial potential profile obtained with an emissive probe. (b) Two-dimensional equipotential contours.

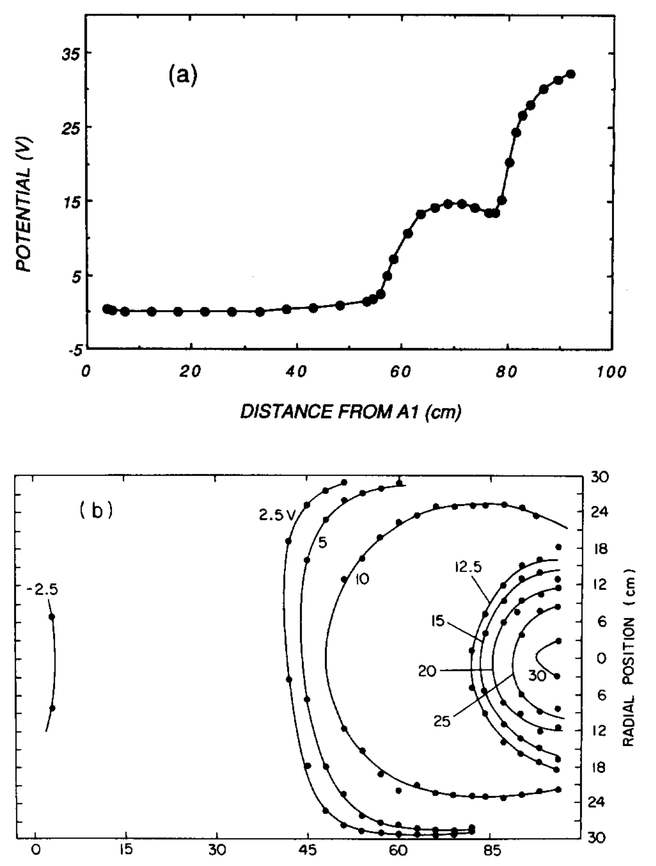

FIG. 3. Double layers produced in a plasma containing positive ions, negative ions, and electrons under the same conditions as in Fig. 1, but with $P(SF_6) = 4\times10^{-5}$ T. (a) Axial potential profile showing two double layers. (b) Two-dimensional equipotential contours.

plasma has some similarities with phenomena observed in high-pressure discharges in electronegative gases. It has long been known that a uniform positive column of positive ions and electrons has a tendency to break up into curved striations when trace amounts of an electron attaching species, such as chlorine or iodine, are added.[1] At the head of each striation there is a double layer of positive and negative charge. This phenomenon has been attributed to the fact that the negative ions, being more massive than electrons, will have a greater tendency to set up regions of negative space charge.[22]

The only theoretical work on strong double layers in negative ion plasmas that we are aware of is that of Breslin and Emeleus.[23] This work is a generalization of Langmuir's original theory of double sheaths.[24] They showed that the general form of the double layer solution obtained by Langmuir was not altered by the presence of any number of positive and negative ion species. From their general results, we derived the "modified" Langmuir condition for a plasma consisting of one positive ion species, one negative ion species, and electrons. This condition, which is typically satisfied for strong stationary double layers, can be expressed in the form

$$\sqrt{m_+}\Phi_+ = \sqrt{m_e}\Phi_e + \sqrt{m_-}\Phi_-, \qquad (1)$$

where Φ_j ($j = +, e, -$) is the positive ion, electron, and negative ion flux through the double layer, and m_j ($j = +, e, -$) is the respective mass. The extension of this result to arbitrary numbers of positive and negative ions is obvious. These results were obtained under the assumption that the fluxes do not change as the particles pass through the double layer, which is not unreasonable since typically the thickness of the double layers is much smaller than any collisional mean-free path. However, the particle fluxes are not likely to be constant over the entire length of the central chamber. The negative ion concentration probably increases (and the electron density decreases) from A1 toward the center of the device as electrons attach to SF_6 molecules to form the negative ions. Under these conditions, it is possible that condition (1) may be satisfied at *two* axial locations simultaneously, so that *two* double layers may form: essentially a positive ion/electron double layer and a positive ion/negative ion double layer.

In summary, we have demonstrated experimentally that strong double layers can be formed in a plasma consisting of positive ions, negative ions, and electrons. Under appropriate conditions the presence of an additional negative particle species in the plasma results in the formation of two double layers with an overall potential drop somewhat larger than that obtained in the positive ion/electron plasma.

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