Experimental Observations of Strong Double Layers

Peter Coakley and Noah Hershkowitz
Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242

and

Richard Hubbard and Glenn Joyce[a]
National Aeronautics and Space Administration/Goddard Space Flight Center, Laboratory for Extrasterrestrial Physics, Planetary Magnetospheres Branch, Greenbelt, Maryland 20771
(Received 18 November 1977)

Strong electric potential double layers ($e\varphi/kT_e \simeq 14$) are produced in a triple plasma device. The upper bound to $e\varphi/kT_e$ reported in earlier experiments is not found. The electron beam which results from acceleration by the double layer maintains its identity with little heating until it reaches the end of the device. Results of a computer simulation are presented which are in qualitative agreement with the experiment and which indicate that the stability of the double layer depends on the length of the system.

In several recent papers strong evidence has been presented for the presence of electric potential double layers (DL) in the low magnetosphere above the auroral zones.[1] Such DL appear to be standing electrostatic shocks with potential jumps $e\varphi/kT_e$ ranging from 10 to 100 and shock front thicknesses the order of a few hundred Debye lengths λ_D. Electrons are accelerated to 10^2–10^4 eV by the DL and observed far from the shock fronts. In contrast to the strong DL ($e\varphi/kT_e \geq 10$) observed in the magnetosphere, only *weak* DL ($e\varphi/kT_e \lesssim 4$) have been observed in laboratory discharge tube experiments over the past ten years.[2] Although double layers were clearly present, detailed structure could not be obtained because of high plasma density ($n \sim 10^{11}$ cm^{-3}) and correspondingly small λ_D. This difficulty was overcome in a recent experiment by Quon and Wong[3] in which they demonstrated that stable DL could be produced in a double plasma device at much lower plasma densities ($\sim 10^8$ cm^{-3}). With λ_D the order of 1 mm, they were able to make detailed measurements of the standing shock by making use of a perpendicular electron test beam, Langmuir probes, and ion energy analyzers.

Quon and Wong found that double layers were produced if the electron drift $v_d \geq v_e$ where $v_e = (kT_e/m_e)^{1/2}$, a condition which was also necessary in previous experiments. The DL were unstable when $v_d > 3v_e$, i.e., when $e\varphi/kT_e \equiv \frac{1}{2}mv_d^2/kT_e > 4.5$. This result amounts to finding that only *weak* DL were stable. Energetic electron beams produced at the double layer were thermalized via beam-plasma interactions within 5–10 cm of the double layer. The reflection of accelerated ions by the grid at the end of the chamber was crucial to the DL formation and stability.

We have investigated the apparent lack of stability of *strong* laboratory DL and have found that $e\varphi/kT_e \lesssim 4.5$ does not always hold. Here we present experimental data for strong DL with $e\varphi/kT_e \approx 14$.

The distinction between weak and strong DL is basically the distinction between electrostatic shocks which involve some steady-state dissipative mechanism (i.e., turbulent shocks) and those which do not. Montgomery and Joyce[4] demonstrated that it was possible for an electrostatic shock to exist without turbulence if a population of trapped electrons was present. The details of particular shock profiles were seen to depend on the details of the trapped-electron distribution function. It was later shown in various computer simulations[5] that shocks with a variety of Mach numbers (and $e\varphi/kT_e$) could be produced depending on the trapped-electron distributions. Knorr and Goertz made use of similar arguments to describe DL.[6]

In previous DL experiments, the trapped plasma electrons have been formed from accelerated electrons downstream from the shock. Such a procedure results in high-energy downstream electrons and does not allow the trapped electrons a wide variety of distribution functions. This apparently results only in the self-consistent formation of weak double layers. We have eliminated this restriction by producing DL in a triple plasma device. The essence of this method is to provide *separately* free and trapped electrons which have been accelerated through the DL to provide trapped electrons.

The University of Iowa triple plasma device is shown schematically in Fig. 1. Plasma was produced in two source chambers each of which is

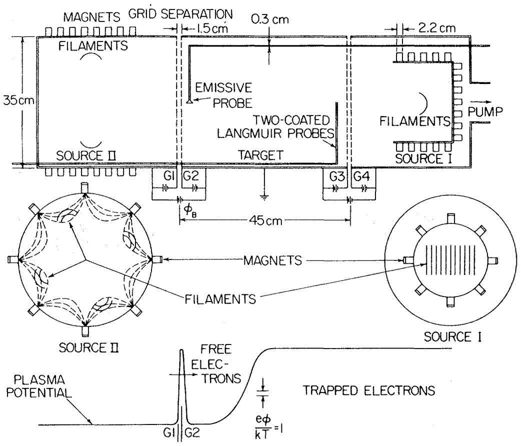

FIG. 1. Schematic of the triple plasma device. Free electrons are produced in source I and trapped electrons are produced in source II. Grids are normally biased at the same potential as their neighboring chamber. In the absence of DL, electrons are accelerated between the closely spaced grids. When DL are present, the acceleration takes place somewhere inside the target chamber. The potentials associated with a typical DL are shown below the device.

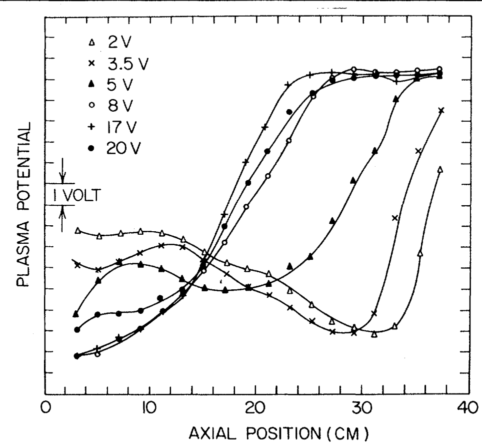

FIG. 2. Potential vs position for various DL as a function of the bias of $G2$ with respect to source I. $G1$, $G3$, and $G4$ were at 0 V and φ_B was at 18 V.

separated from the central target region by two separation grids (100 mesh spaced at 1.5 cm). Plasma in the trapped-electron source chamber (I) is produced by filaments in a magnetic-field–free region surrounded by a full-line-cusp permanent magnet grid. Plasma in the "free" electron chamber (II) is produced by filaments which are placed so that ionizing electrons are *trapped* by the surface magnetic field. This prevents the ionizing electrons in that chamber from accelerating across the double layer and ionizing atoms in the target. It was difficult, though not impossible, to produce DL when ionizing electrons were not trapped. Grids were normally biased at the potential of the nearest chamber (as shown in Fig. 1).

Electron distribution functions were monitored using a collecting Langmuir probe while the plasma potential was determined using an emissive Langmuir probe.[7] Emissive probes were found to provide a reproducible and accurate way of determining the local plasma potential. The resolution was limited by the probe temperature (~ 0.2 eV) and so was much more accurate than a collecting Langmuir probe (with the large $\lambda_D \approx 1.5$ mm of the experiment). The emissive probe is also much easier to use than the perpendicular electron beam probe used previously.[3] Typical operating parameters were $n_i \sim 3\times10^7$ cm^{-3} and T_e ~ 1.0 eV. DL could be obtained with neutral pressure of argon plasma $3\times10^{-5} < p < 3\times10^{-4}$ Torr. Typical ionizing electron energies were 50 eV in source I and source II.

Typical results are shown in Fig. 2. It was found that the bias of the target grid $G2$ at the free-electron source and of the target chamber were important parameters in establishing stable DL. As Quon and Wong reported it was possible to eliminate the DL by biasing this grid negative with respect to the target. More interestingly, we found that the position, size, and thickness of the DL varied as the bias voltage of $G2$ was changed. With $G2$ biased at the target potential a DL with $e\varphi/kT_e = 14$ was obtained. This DL represents a "local maximum" in the DL potential step that could be obtained by making small changes in operating parameters. It was easy to achieve and quite reproducible. DL with much greater $e\varphi/kT_e$ were obtained occasionally but not in a reproducible way. Variations similar to those shown in Fig. 2 in DL position, size, and thickness could be obtained by varying the free-electron-source–target-chamber bias voltage and plasma densities.

Differentiated collecting Langmuir probe traces, essentially $f(E)$ vs E, were measured to determine whether the accelerated electrons were thermalized. These curves were corrected for the local plasma potential determined by the emissive probe to give $f(E)$ vs v. The results corresponding to a DL produced with $G2 = 12$ V are shown in Fig. 3. It is apparent that the accelerated electrons do *not* thermalize at least

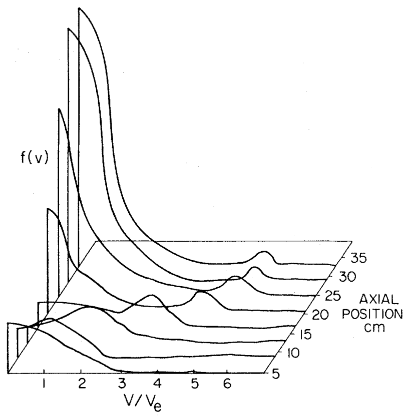

FIG. 3. Electron distribution functions at various axial positions of the target chamber. Note that electrons accelerated at the DL do not thermalize and are well separated from the trapped electrons.

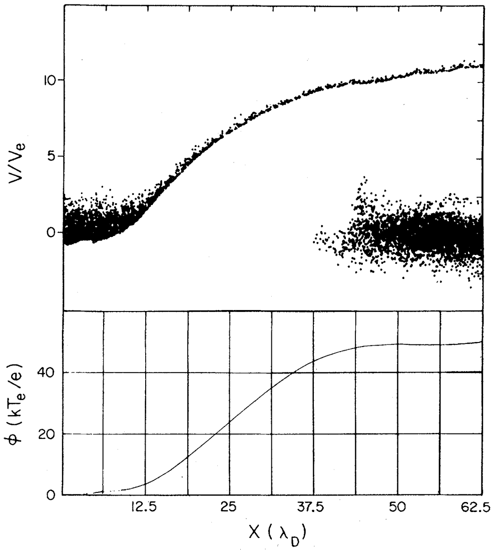

FIG. 4. Upper plot, phase-space plot of electrons taken from the computer simulation at $t \simeq 95\omega_{pe}^{-1}$. The system length was $62.5\lambda_D$, the mass ratio was 128:1, and there were 6000 electrons and 6000 ions. The potential difference across the system was $50kT_e/e$. Lower plot, the electrostatic potential vs distance under the same conditions.

over a distance of 30 cm and that electron flux is conserved. The electron distribution function downstream from the DL is double humped and one might expect that it is unstable. We believe that the apparent stability is the result of insufficient space in the device downstream of the DL for instabilities to wipe out the DL.

This hypothesis was checked by running a series of one-dimensional PIC (particle-in-cell) particle simulations. Conditions were similar to those of the experiment although $e\varphi/kT_e$ was considerably larger in the simulations. Details of the simulation will appear elsewhere.[8] The plasma was modeled as consisting of three regions, the middle region being the one simulated. The outer two regions were large reservoirs of Maxwellian plasma which could drift into the central plasma. Charge neutrality was maintained by replacing each particle which left the simulation plasma by a particle which "wandered" in from one of the reservoirs. A constant, external potential difference was imposed on the central plasma and the profile of the potential and the details of the particle populations were monitored as time progressed. Figure 4 shows the electron phase space and the potential profile at a single time for $e\varphi/kT_e = 50$ and a system length of $62.5\lambda_D$. It is apparent that cuts across the phase-space plot at various positions would produce distribution functions quite similar to those seen experimentally in Fig. 3. The accelerated electrons do not thermalize in these rather short systems.

We found that for longer system lengths the beam-plasma interaction downstream from the DL tended to destabilize the system resulting in the disruption of the double layer and in considerable beam and plasma heating. It appears that the condition for the beam-plasma instability is given approximately by $L > 2\pi(2e\varphi/kT_e)^{1/2}\lambda_D$, where L is the distance from the downstream side of the DL to the end of the system. For the DL produced in the TP device the downstream distance to $G3$ was about three times as large as L. The laboratory boundary conditions were sufficiently different from the simulation conditions that quantitative agreement can hardly be expected. Nevertheless, Fig. 4 is in good qualitative agreement with Figs. 2 and 3.

In summary, we have shown that *strong* DL can be produced in a triple plasma device. The key to achieving strong DL is to separate the production of free and trapped electrons. In this respect, the triple plasma technique is different from that used in previous experiments. It is not surprising to us, in retrospect, that the properties of DL depend on the details of the trapped-electron distribution function since such a dependence is well established for propagating electrostatic shocks. The DL potential ($e\varphi/kT_e$) is not found to have the upper threshold reported in earlier experiments. The electrons accelerated by strong DL are not thermalized in our triple plasma device. The results of the computer simulation which we have presented indicate that the size of the "device" plays a role in determining which DL are stable.

We thank Alfred Scheller for construction and reconstruction of the triple plasma device. We also thank Dr. Stanley Shawhan and Dr. Nicola D'Angelo for a number of useful discussions and Dr. B. H. Quon for providing details of the experiment described in Ref. 3. This work was supported by the Atmospheric Research Section and by the Engineering Division of the National Science Foundation. One of us (R.H.) is a National Academy of Science/National Research Council Research Associate.

[(a)]Permanent address: Department of Physics and Astronomy, University of Iowa, Iowa City, Ia. 52242.

[1]F. S. Mozer, C. N. Carlson, M. K. Hudson, R. B. Torbert, B. Parady, J. Yatteau, and M. C. Kelley, Phys. Rev. Lett. 38, 292 (1977); E. M. Wescott, H. C. Stenback-Nielsen, T. J. Hallinern, and T. N. Davis, J. Geophys. Res. 81, 4495 (1976); L. P. Block, Cosmic Electrodyn. 3, 349 (1972); L. P. Block, private communication, 1977; S. D. Shawhan, C.-G. Fälthammer, and L. P. Block, University of Iowa Report No. 77-25, 1977 (unpublished).

[2]D. Anderson, Department of Electron Physics, Royal Institute of Technology, Sweden, Report No. TRITA-EPP-76-10, 1976 (unpublished); S. Torven and M. Babic, in *Proceedings of the Twelfth International Conference on Phenomena in Ionized Gases, Eindhoven, The Netherlands, 1975*, edited by J. G. A. Hölscher and D. C. Schram (American-Elsevier, New York, 1975), Pt. 1, p. 124.

[3]B. H. Quon and A. Y. Wong, Phys. Rev. Lett. 37, 1393 (1976).

[4]D. C. Montgomery and G. Joyce, J. Plasma Phys. 3, 1 (1969).

[5]D. W. Forslund and J. P. Friedberg, Phys. Rev. Lett. 27, 1189 (1971); J. S. DeGroot, C. Barnes, A. E. Walstead, and O. Buneman, Phys. Rev. Lett. 38, 1283 (1977).

[6]G. Knorr and C. K. Goertz, Astrophys. Space Sci. 31, 209 (1974).

[7]F. F. Chen, *Plasma Diagnostic Techniques*, edited by R. H. Huddlestone and S. L. Leonard (Academic, New York, 1965), p. 113.

[8]R. Hubbard and G. Joyce, to be published.

Korteweg–de Vries Soliton in a Slowly Varying Medium

K. Ko and H. H. Kuehl
University of Southern California, Los Angeles, California 90007
(Received 30 June 1977)

We derive an approximate solution to the Korteweg–de Vries equation with slowly varying coefficients for a soliton initial condition. Expressions are given for the amplitude, position, and velocity, and it is shown that the soliton experiences an irreversible loss of energy whenever it travels in a slowly varying medium. These results are applied to an ion acoustic soliton in a nonuniform plasma and are confirmed by comparison with the results of numerical integration of the differential equation.

The Korteweg–de Vries (KdV) equation arises in the study of various weakly nonlinear dispersive systems, e.g., shallow-water waves[1] and ion acoustic waves in plasmas.[2] Great interest in the KdV equation has been generated by the exact solutions found by Miura, Gardener, and Kruskal.[3] In many physical systems it is common that the medium in which a disturbance travels varies, e.g., the depth of a channel in which water waves travel is not constant, or the unperturbed plasma density in which an ion acoustic wave propagates is a function of position. We therefore present here the results of a theoretical and numerical study of a KdV soliton in a slowly varying medium. The theoretical technique is based on a perturbation expansion of the variable-coefficient KdV equation where we assume that the scale on which the soliton varies is short compared to that on which the medium varies. Other attempts[4,5] have been made to predict the behavior of a KdV soliton in a slowly varying medium but these are in error. Our solution differs from those of previous workers in that it shows for the first time that a KdV soliton loses energy whenever it travels in a slowly varying medium, independently of how the medium varies.

We consider a soliton governed by the KdV equation with slowly varying coefficients,

$$u_t + \alpha(T) u u_x + \beta(T) u_{xxx} = 0, \quad \alpha, \beta > 0, \tag{1}$$

where the coefficients α and β are arbitrary positive functions of a slow time variable $T = \epsilon t$, with