Oblique Double Layers: A Comparison between Terrestrial and Auroral Measurements

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The S3-3, POLAR, and FAST satellite auroral observations of parallel and perpendicular electric field structures have been identified as belonging to a large "*U*"-shaped potential structure that supports oblique electric double layers. This interpretation is verified by terrestrial laboratory measurements of a self-consistently supported three-dimensional oblique current-free double layer. Its width is a few tens of Debye lengths, its oblicity (with respect to the magnetic field) varies from 0 up to 30°, and its strength is a few times the electron temperature.

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Large perpendicular electric fields (called electrostatic shocks) measured by the S3-3 satellite [1] were the first signature of a converging potential structure and hence of parallel electric fields in the auroral acceleration region. These localized parallel electric fields have since been directly measured by the S3-3 [2,3], POLAR [4], and FAST [5] satellites. Statistical analysis of parallel and perpendicular electric field and accelerated charged particle flux data recorded during POLAR and FAST satellite paths across the auroral cavity strongly support the possibility of an electric double layer (DL) in the two auroral transition layers [6]. The upward auroral current (inwards pointing electric fields, antiearthward ion beam, and earthward electron beam producing the visible auroral arcs) is generated in the low altitude transition layer [6], and the downward auroral current (outwards pointing electric fields, earthward ion beam, and antiearthward electron beam of the nonvisible aurora) is generated in the high altitude transition layer [7] schematized in Fig. 1(a).

Many scientists have speculated whether the equipotentials are closed rather than open ended [8], and a possible scenario is that suggested by Ergun *et al.* [6,7], i.e., a large scale cavity with equipotentials at each end in the form of double layers. The implication is that the double layers can exist in weakly diverging or converging magnetic fields and the higher potential can be at a higher magnetic field. This is important for the present research as the double layer in the laboratory is found in a weakly diverging magnetic field, whereas Fig. 1(a) shows a weakly converging magnetic field. The structure can take the form of various *U*-shaped pocket intrusions (with the field pointing inwards or outwards) of the magnetosphere into the ionosphere [4,9].

Here the aim was to create in the laboratory a similar situation to that of the auroral model of Fig. 1(a), using a new oblique current-free double layer represented in Fig. 1(b), where the accelerated ions move along the diverging magnetic field. The low potential edge of the DL and the accelerated ion beam current j^+ measured in the laboratory are shown in Fig. 2. This result was achieved by constructing the apparatus shown in Fig. 3 ("nonstretched" z axis) which consists of a Pyrex tube surrounded by a Helicon antenna ($z = 3$ and 21 cm) and two axial solenoids ($z = 1.5$ and 21 cm) and is mounted on an earthed aluminum diffusion chamber [10]. The system is pumped down to a base pressure of $\sim 2 \times 10^{-6}$ Torr, and, rather than argon, the molecular gas CO_2 was chosen as being closer to conditions existing in the aurora. The rf power is maintained at 250 W. A magnetic field decreasing from a maximum of about 0.0142 T in the source ($z = 20$ cm) to about 0.001 T in the middle of the diffusion vessel ($z = 45$ cm) is used [10]. The laboratory probes consist of a 1 mm-diam planar Langmuir probe (LP) biased at -55 V to measure the plasma density, a 0.25 mm-diam 3 mm-long cylindrical rf compensated Langmuir probe to measure the electron temperature, and a retarding field energy analyzer (RFEA) with a 2 mm-diam aperture hole to simultaneously

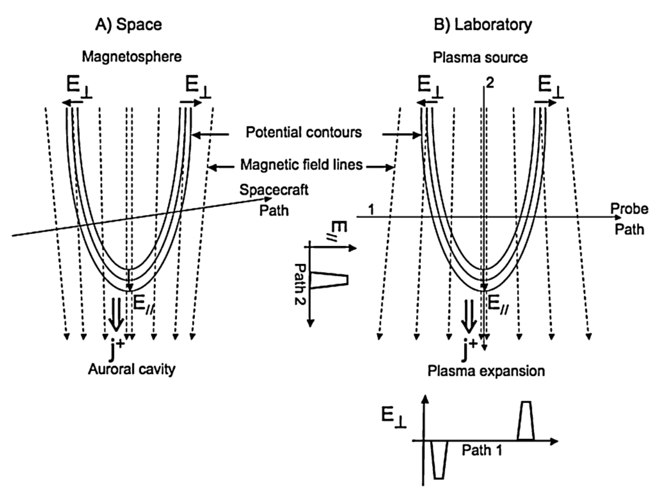

FIG. 1. A schematic interpreting the observations from (a) the FAST satellite traveling through the downward current region and (b) the laboratory probe traversing the experimental double layer; j^+ represents the downward accelerated ion current.

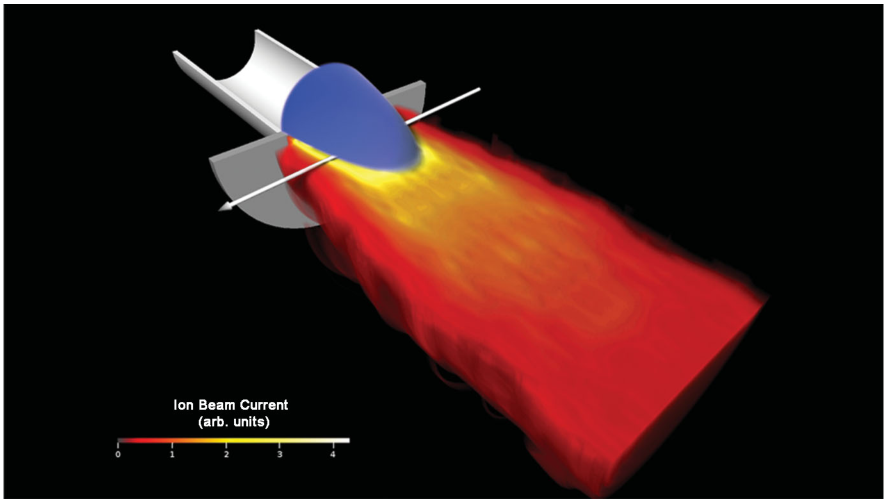

FIG. 2 (color). A "3D" color plot of the *U*-shaped current-free double layer (blue "dome") and accelerated ion beam current (yellow to red "flame") measured in the laboratory experiment using the RFEA. A typical probe path is shown by the gray arrow. The plasma source tube and source-chamber interface plate are shown in gray. The main axis has been stretched by a factor of 3 for visualization purposes, a common stratagem in auroral physics.

measure the plasma potential and ion beam current [10]. The RFEA can be mounted on two separate support tubes (support tubes 1 and 2 in Fig. 3), and the paths were specifically chosen so as to simulate POLAR [4,11] and FAST [6,7] satellite paths across the auroral region (paths 1 and 2 in Fig. 1). The electric field is obtained by differentiating the potential along each probe path.

Figures 4(a) and 4(b) show the measured plasma potential and electric field along path 1 ($z = 32$ cm) for operating rf power and gas pressure conditions of 250 W and 0.04 Pa (0.3 m Torr), respectively: A typical perpendicular electric field structure showing a negative and positive excursion corresponding to a path across a converging potential structure is clearly obtained. This structure is similar to the first observation of paired electrostatic shocks in the polar magnetosphere [1] and to more recent observations [6,11,12]. Space data are usually plotted versus time which linearly scales with the distance along the satellite path. Here the abrupt drop in potential by about 10 V at about $x = -1.5$ and $x = 1.5$ cm is the electric double layer demonstrating the symmetry of the potential structure about the z axis. Figures 4(c) and 4(d) show the measured plasma potential and electric field along path 2 ($x = 0$ cm) for an operating rf power of 250 W and a slightly higher gas pressure of 0.053 Pa (0.4 m Torr). This structure is similar to localized auroral parallel electric fields measured by S3-3 [3], POLAR [4], and FAST satellites [5,7,12]. Again, the potential drop of about 10 V at $z = 34$ cm is the electric double layer.

A detailed spatial study of the plasma potential and accelerated ion beam is carried out on the whole half-space of the apparatus using the RFEA mounted on the dogleg support tube 2. Mapping is obtained with the RFEA rotating on its support tube axis every 5° ($x = -14$–0 cm) for each value of z ($z = 30$–49 cm every centimeter). The whole space is obtained by mirroring the data since the radial symmetry has been verified by the earlier experiments [Fig. 4(a)]. The plasma potential and perpendicular electric field data following a trajectory along the x axis at $z = 32$ cm are shown in Figs. 4(e) and 4(f) for the 0.053 Pa (0.4 m Torr) operating pressure case (rf power of 250 W). The double layer is seen at about $x = -4$ cm. Here the results obtained at 0.053 Pa (0.4 m Torr) show perpendicular and parallel electric fields of comparable magnitude. Figure 5 shows the measured plasma equipotential contours in the region of interest ($z = 30$–38 cm). The low

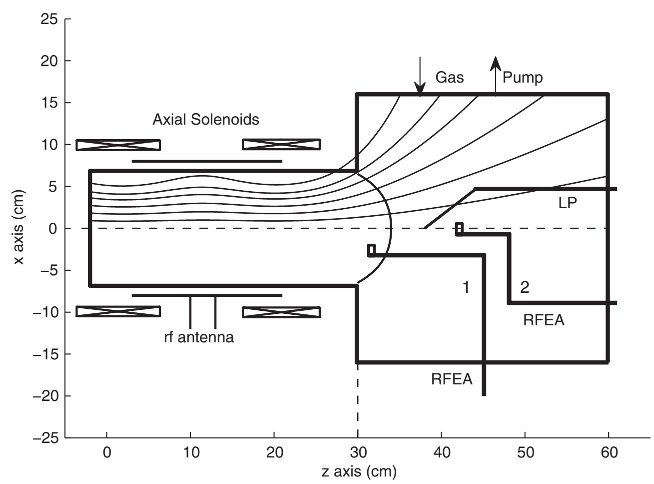

FIG. 3. Schematic of the expanding plasma apparatus showing the probes and the low potential edge of the double layer (solid line).

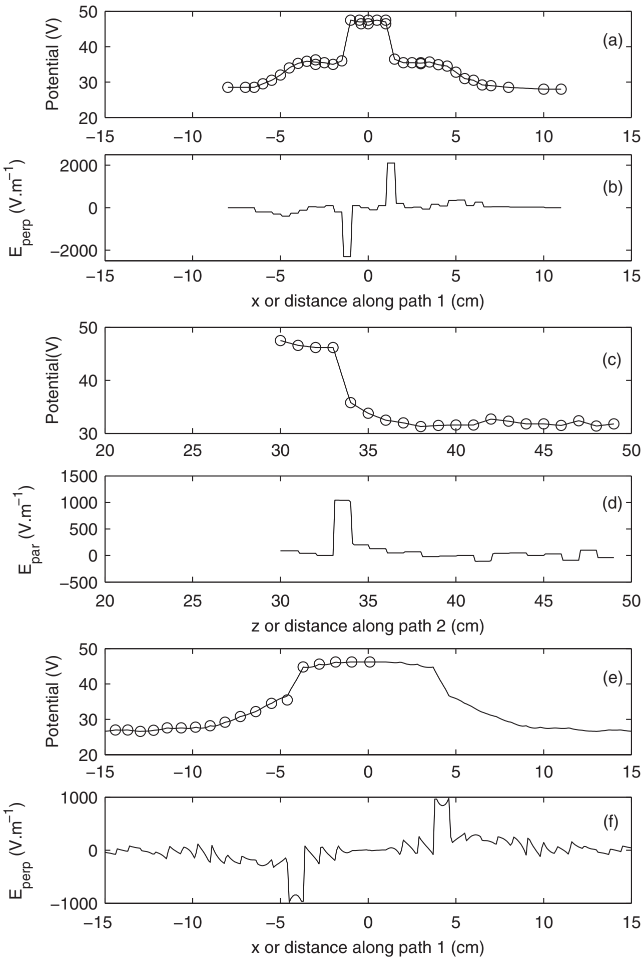

FIG. 4. Laboratory data (open circles) and fit (solid lines) obtained along various paths: (a) plasma potential and (b) perpendicular electric field along path 1 for $z = 32$ cm for 250 W and 0.04 Pa (0.3 m Torr); (c) plasma potential and (d) parallel electric field along path 2 for $x = 0$ cm (central axis) for 250 W and 0.053 Pa (0.4 m Torr); (e) plasma potential and (f) perpendicular electric field along path 1 for $z = 32$ cm for 250 W and 0.053 Pa (0.4 m Torr).

potential edge of the DL is fitted by a parabola which corresponds to $z = 34$ cm on the central axis ($x = 0$ cm). All equipotentials upstream ($V_p \geq 46$ V), within ($36 \leq V_p \leq 46$ V), and downstream of the double layer ($36 \geq V_p \geq 32$ V) exhibit a convex shape. There is no measurement within the DL, and the contours result from the interpolation. The results are consistent with the schematic proposed for the aurora [Fig. 1(a)] and provide the first laboratory experimental evidence of the schematic shown in Fig. 1(b). To visualize the correct oblicity of the DL, a zoom of the nonstretched DL is shown in Fig. 6 along with the magnetic field lines: The shape of this double layer is that of a "U," and the electric field of the DL is aligned with the magnetic field near the z axis and moves away from the magnetic field by up to 30° near

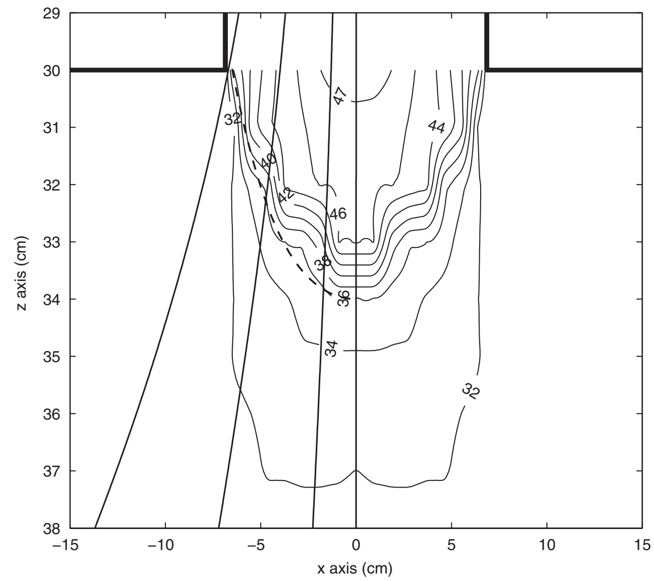

FIG. 5. Two-dimensional equipotential contours measured with the RFEA for 250 W and 0.053 Pa (0.4 m Torr) showing the low potential edge (fit in dotted line).

the source tube. This oblicity is less than that reported in more elongated U-shaped laboratory DLs [13,14].

Figures 4(c) and 4(e) show that the spatial coordinates of the low potential edge of the DL are $(x, z) = (4.7, 32)$ along path 1 and $(x, z) = (0, 34)$ along path 2, respectively. Along both paths the DL width is about 1 cm (or less since the resolution of the mapping is 1 cm), and the perpendicular and parallel electric fields are comparable and about 1000 $\mathrm{V \cdot m^{-1}}$. At the low potential edge of the DL, the density measured with the Langmuir probe is 6.3×10^9 cm^{-3} along path 1 and 6.1×10^9 cm^{-3} along path 2. This corresponds to a Debye length of about 0.027 cm. Hence the estimated DL width is about $37\lambda_D$ (Debye length) or less. This is in good agreement with estimations for the auroral double layer of about $10\lambda_D$ [7], $20\lambda_D$ [11], and $40\lambda_D$ [15] using space observations and related simulations. Here the magnetic field is 0.0047 T at $(x, z) = (4.7, 32)$ and 0.0039 T at $(x, z) = (0, 34)$, respec-

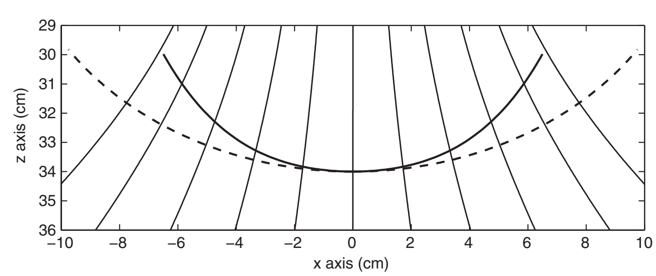

FIG. 6. A simplified nonstreched representation of the oblique current-free double layer (thick solid line). The dotted line corresponds to the perpendicular of the magnetic field lines passing through $z = 34$ cm and $x = 0$ cm.

TABLE I. Plasma parameters measured for $x = 0$ cm near the DL edges (at $z = 30$ and 36 cm); the ion-neutral collision length is about 10 cm.

Parameter	Upstream	Downstream
B (T)	7×10^{-3}	2.6×10^{-3}
n_e (cm^{-3})	7.8×10^{9}	6.7×10^{9}
T_e (eV)	8 (trapped), 4.5 (free)	4.5
T_i (eV)	0.2	0.2 (thermal), 10 (accelerated)

tively, which leads to an estimated ion Larmor radius of about 7 cm, which is larger than the DL width. The potential drop of the double layer is about 10 V for the present operating conditions. Since the electron temperature measured downstream of the DL is about 4.5 eV, the strength of the DL is about $2.2T_e$. Table I gives a summary of the plasma parameters. Recently, the space experiment of Ergun *et al.* [7] showed direct observations of a magnetic-field-aligned (parallel) electric field which forms a localized potential gradient of roughly $10\lambda_D$ along the magnetic field which is consistent with double layer formation, with an inferred strength of $\Delta\phi_{DL} = 3$–$5T_e$ where T_e (6 eV) is the measured ''heated'' electron population on the low potential side and $\Delta\phi_{DL}$ (30 V) is derived from the electric field measurements. The width of the U in the present experiment is likely related to the diameter of the plasma source tube. For the potential contour at 46 V (upstream edge of the DL), the width varies between about 2 and 6 cm ($z = 33$–30 cm) and is 2–6 times greater than the DL width of 1 cm (Fig. 5). A ratio of 3 between the width of the U (30 km) and the acceleration region (10 km) has been reported for the aurora [4], although it is not presently known if there is an equivalence between the sources of curvatures in the laboratory and in space.

In summary, we have shown the first evidence of a current-free double layer U-shaped potential structure and simultaneously measured accelerated ion beam. The results are in consort with recent space observations.

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