The Search for Double Layers in Space Plasmas

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Localized, quasi-static parallel electric fields that are created as a result of charge separation in plasmas have been studied by scientists over the last century and have become known as double layers (DLs). DLs are important because they can efficiently accelerate charge particles, dissipate energy, and cause a local break in the frozen-in condition. As a result, they are expected to be an important process in many different types of space plasmas on Earth and on many astrophysical objects. This paper presents a brief review of the history of DLs over the last century leading to the now well-established fact that they do occur naturally in space plasmas. The paper also presents some of the latest understanding of the basic properties of DLs in the aurora region and discusses some open research questions.

1. INTRODUCTION

A simple yet very effective way to accelerate charge particles is through a parallel electric field. However, charge particles have high mobility along the magnetic field, so it was believed that a parallel electric field would vanish rapidly. As a result, Hannes Alfvén formulated the frozen-in concept [*Alfvén*, 1950]. Later on, he regretted that he created this concept as he realized that localized charge separation could develop as a self-consistent plasma structure and that these structures could have a major effect on the global system with, for instance, slippage of flux tubes [*Alfvén*, 1958]. A localized charge separation with a net potential is now called a double layer (DL).

Two characteristic signatures are associated with DLs: particle acceleration and energy dissipation. These features make the DL very interesting in many different plasma environments spanning from laboratory experiments to astrophysics. There have been several reviews describing the fundamental physics associated with the DL, to which the reader is directed for a better physical understanding [*Block*, 1978; *Swift*, 1978; *Sato*, 1982; *Schamel*, 1986; *Raadu*, 1989].

With the writing of this article, it became clear that one possible area of confusion is that there are different types of DLs. In collisionless plasma, there are surface, current, and gradient types of DLs. A surface DL is created by currents to and from the surface, which results in a sheath between the surface and the plasma that may carry a net potential. Examples of surface DLs are probe/sensor interaction with plasmas [*Langmuir*, 1929], spacecraft interaction with space plasmas, and the Moon's interaction with the solar wind [*Halekas et al.*, 2003]. A gradient DL (or currentless DL) is associated with strong magnetic and/or density gradients resulting in charge separations [*Charles*, 2009; *Scime et al.*, 2010]. This type of DL is being studied actively as a potential application to ion thrusters. Finally, the current-driven DL is a result of interaction between two different plasma regions with a strong, field-aligned current. If the drift between the electrons and ions is large enough, two-stream [e.g., *Buneman*, 1959] instabilities can develop, which can lead to DLs. In this chapter, we focus on the last of these types of DL.

In current-driven plasma, there are several structures that are, on occasion, called DLs. As described by *Raduu* [1989], quasi-static theoretical descriptions for potential structures exist for solitary potential structures (e.g., electron/ion phase

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space holes), slow ion acoustic DL, weak DL, and strong DL, etc. The focus of this chapter is on strong DL since they are very effective in accelerating particles and in dissipating energy.

Bernstein et al. [1957] derived a method to solve the Vlasov equation for self-consistent, stationary potential structures. The current-driven, quasi-static strong DL can be described as a Bernstein-Greene-Kruskal (BGK) solution. The particle populations that are required to maintain this structure include two "passing" populations and two "trapped" (reflected) populations (see Figure 1). The size of the structure is of the order of the square root of the mass ratio times the Debye length [*Block*, 1978]. Note that, since the plasma conditions can change dramatically across a DL, the Debye length can be difficult to define.

These quasi-static structures require two specific conditions: charge separation and pressure balance. The charge layers form with the correct polarity if the inflow from both sides meets the Bohm criterion [*Bohm*, 1949].

This criterion describes that to get a charge separation, additional reflected populations are required such that the time for the different populations to pass through the location of the charge separation results in a charge separation.

The pressure balance is met if the structure is in a frame in which the ion-to-electron current ratio meets the Langmuir condition [*Langmuir*, 1929; *Block*, 1972].

The difference between the weak DL and the strong DL is the relationship between the inflowing particle thermal speed (v_{th}) and the accelerated outflowing particle drift (v_d). The Langmuir condition describing the pressure balance means that a strong DL can exist in the frame where the ratio between the ion and electron current is equal to the square root of the ratio of the electron to ion mass.

For a strong DL ($v_d > v_{th}$), an unstable particle beam emerges from the DL leading to further instabilities and potential heating of the beam. As such, strong DLs are associated with waves and nonlinear features. Fundamentally, a DL is not necessarily a static structure, that is, its behavior may depend on the waves and nonlinear structures that it creates.

When describing a system associated with DLs or modeling a DL, one can start with a prescribed large-scale potential in the system or a prescribed current driving the system. Ultimately, the DL acts as the load (resistor) in the system, whereas the energy source is described as a current generator or a voltage generator. To understand the behavior of the DL (the load), one does not necessarily need a clear understanding of the energy source.

There are situations in dynamic simulations, laboratory experiments, and space observations in which the observed DL behaves as a structure that is well described by the static BGK DL solution. In these cases, we call the structure a "laminar" DL. Instabilities can still act on either side of the DL as long as the DL itself is slowly evolving in time. A "turbulent" DL, which has been identified in simulation results [*Newman et al.*, 2008], has a localized potential jump (i.e., localized parallel electric field), but the instabilities on one or both sides are so significant that they interact with the localized potential jump, and the DL is difficult to identify in the data.

The remainder of this article has the following layout. The history of DLs will be presented in chronological order with some major milestones over the last century. This is followed by a discussion of recent observations, our current understanding, and outstanding questions we have today.

2. EARLY 1900

Irving Langmuir, working for the General Electric Company in Schenectady, New York, was one of the first researchers to investigate surface-plasma interactions leading to the basics of charge separation. In work associated with surface-plasma interaction, he realized that a charge separation could develop resulting in a parallel electric field. This potential structure was called a "double sheath." *Langmuir* [1929] constructed the first self-consistent DL solution with cold particles (delta-function distributions) and experimented with current-driven discharge tubes. This early work formed the basis of the space applications today such as Langmuir probes and DL theories.

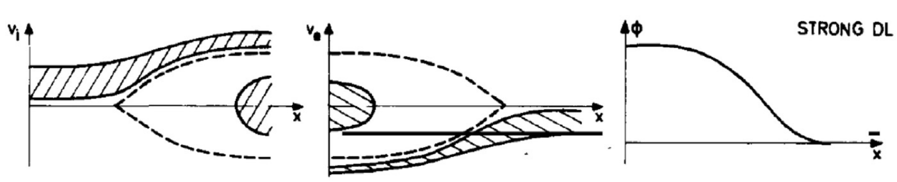

Figure 1. (left) Ion and (middle) electron-phase space diagrams for a strong double layer. Reprinted from the first part of Figure 3 of *Raadu* [1989], with permission from Elsevier. (right) The potential profile. The separatrices for the particle motions are shown as dashed lines. The diagrams illustrate that both ions and electrons have distinct passing-through and trapped populations.

3. THE ERA OF THEORY AND EXPERIMENTS (~1960)

The peak activity of laboratory research on DLs was in the 1950–1970 period. One of the early problems with DLs was their stability [*Block*, 1972; *Knorr and Goertz*, 1974]. Thus, many experiments were developed to see how DLs are created and how to control them [*Block*, 1978]. Another significant step in DL research was made when it became apparent that a DL could form completely within the plasma. A surface sheath was not needed. One way to create the DL was through the Buneman instability [*Buneman*, 1959]. This process appeared to have some type of threshold and, when triggered, was very efficient in accelerating particles. It was immediately recognized that a free-standing DL could be important in space plasmas. Its implication to space plasmas was investigated in several applications such as solar flare eruptions [*Block*, 1972; *Hasan and ter Harr*, 1986] and disruption associated with substorms [*Alfvén*, 1977; *Stenzel et al.*, 1982].

Alfvén became one of the most vocal spokesmen about the impact of DL on astrophysical objects and cosmology [*Alfvén*, 1977, 1982, 1990]. Others did more direct applications to regions such as the solar corona providing alternative methods to the BGK solution and further improvements of the theoretical descriptions [*Montgomery and Joyce*, 1969; *Block*, 1972; *Swift*, 1975; *Perkins and Sun*, 1981; *Williams*, 1986; *Sato and Miyawaki*, 1992; *Boström*, 2004].

Some of the earliest applications of numerical simulations were directed toward understanding of DLs in plasmas. Since most laboratory experiments were set up as a voltage generator, the early simulations focused on that setup [*Goertz and Joyce*, 1975; *Singh*, 1982; *Borovsky and Joyce*, 1983; *Hudson et al.*, 1983; *Lembege and Dawson*, 1989; *Borovsky*, 1992; *Singh et al.*, 2005]. Later simulations are based on current generation in the aurora region [*Newman et al.*, 2001] and in relativistic astrophysical plasmas [*Dieckmann and Bret*, 2009].

4. THE ERA OF SPACE OBSERVATIONS (~1970)

Following the success in the laboratory, space plasma physicists investigated the possibility of DLs in space. Analysis of auroral emissions indicated that the precipitating particles were accelerated. Direct observation of particles verified that the accelerated electrons were nearly monoenergetic, so the possibility that the electrons were accelerated by discrete potential structures was put forth [*Albert and Lindstrom*, 1970]. A DL is a natural candidate to carry the parallel electric field, so the search for strong DLs in the aurora was on.

Analysis of the precipitating auroral electron spectra identified a primary electron beam and secondary (scattered) electrons. The scattered electrons that were moving antiearthward appeared to be a reflection by a parallel electric field [*Evans*, 1974]. This hypothesis ignited a debate on whether the electric field was extended or localized along the magnetic field. A theoretical description of the correlation of field-aligned currents with potential was developed by *Knight* [1973], who showed that a large-scale electric field develops naturally as a result of the combination of a magnetic mirror force and a current. The possibility of a DL, however, was not ruled out.

The next major piece of evidence came from satellites with particle observations and measurements of the perpendicular electric field. The observations suggested that the satellite crossed through a U-shaped potential [*Gurnett*, 1972] as shown in Figure 1.

While particle and field measurements suggested parallel electric fields, topside sounder experiments uncovered strong-density cavities in the topside of the *F* region [*Calvert*, 1966] and low-density cavities at high altitudes [*Hagg*, 1967; *Herzberg and Nelms*, 1969]. In situ observations identified that the density gradients were associated with perpendicular electric fields of possible potential structures [*Mozer et al.*, 1977]. However, large electric fields were also found when no density gradients were present. The observed large density gradients are easily explained by DL theory [*Block*, 1978], but the evidence was not conclusive at that time.

Active experiments using barium clouds released from sounding rockets also were used to study auroral plasmas. Some of the barium cloud/jet experiments investigated perpendicular electric fields [*Wescott et al.*, 1976] with the implication that a DL could explain the observed motion of the cloud and the existence of parallel electric fields [*Haerendel et al.*, 1976].

5. THE ERA OF WEAK DL (~1980)

The S3-3 satellite brought high-resolution observations of paired converging perpendicular DC electric fields called electrostatic shocks [*Mozer et al.*, 1977]. These structures were associated with electrostatic ion cyclotron waves and turbulence. The S3-3 satellite also made the first direct measurement of the parallel electric field associated with the paired electrostatic shocks. This measurement was possible using the 3-D electric field observations on the S3-3 satellite [*Mozer et al.*, 1977]. However, the observed parallel electric field was not convincingly in agreement with DL theory.

One of the most definitive measurements of a parallel electric field in space was an uncovering of small-amplitude electric field structures identified as weak DLs [*Temerin et al.*, 1982]. The weak DL was a bipolar structure with a small net potential, roughly a few volts. The idea that followed was that a large number (thousands) of weak DLs could produce the required net potential (kilovolts) that was inferred from the particle observations. However, a search for weak DLs leads to an estimate far below the required number. While weak DLs were an interesting phenomenon, they did not account for auroral acceleration [*Boström et al.*, 1988; *Boström*, 1992].

6. THE LOSS OF FAITH (~1990)

With no direct measurement of large localized parallel electric fields in space plasma, space plasma researchers started to come up with alternative explanations for the observations. Some publications questioned the existence of quasi-static parallel electric fields and DLs [*Bryant et al.*, 1992], but DLs were still viewed as an important candidate [*Borovsky*, 1992].

With new and exciting observations, the aurora research focused on other issues such as the effect of Alfvén waves and how ions are heated, resulting in atmospheric loss. This decade moved the research forward in many other areas but not much in understanding DLs.

7. THE ERA OF STRONG DL (~2000)

Roughly 70 years after Langmuir's work, the Polar [*Mozer and Kletzing*, 1998; *Mozer and Hull*, 2001] and FAST satellites [*Ergun et al.*, 2001; *Andersson et al.*, 2002] identified unipolar electric fields well above the instrument uncertainties. The FAST observations were accompanied by evidence of localized electron acceleration.

The first positively identified DLs through particle and electric field measurements were observed in the downward current region as a result of the DLs' antiearthward motion [*Ergun et al.*, 2001]. This motion, or the frame of the DL, was shown to be consistent with the Bohm and Langmuir conditions [*Smith and Goertz*, 1978]. The DL-accelerated electron beam was found to create waves and nonlinear plasma structures as result of electron-electron instabilities.

Two such observations can be seen in Figure 2, marked by vertical lines. The turbulent region prior to the DL almost always contains VLF waves and electron-phase space holes. The waves on the high-potential (high-altitude) side are believed to create the commonly observed VLF saucers [*Ergun et al.*, 2003]. This can be used as a remote signature of a DL. As the result of the waves and nonlinear structures, the electron beam undergoes rapid thermalization creating

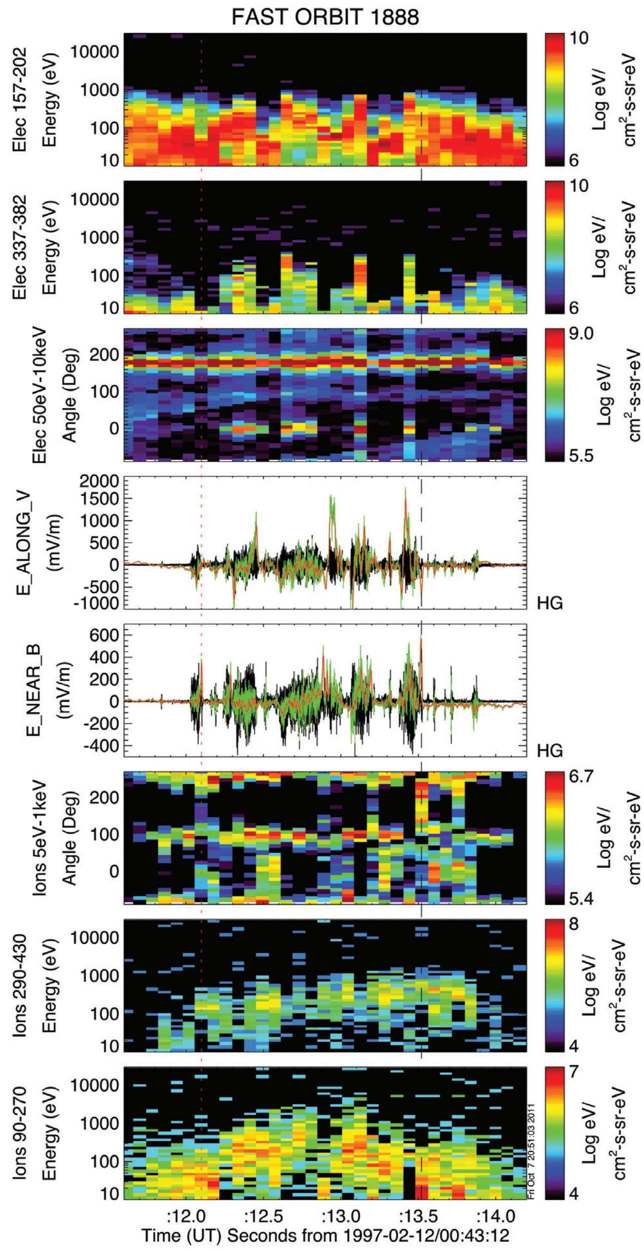

Figure 2. Multiple double layers (DLs) in the downward current region of the aurora. The top three panels are electron spectrograms and the bottom three panels are ion spectrograms. (top to bottom) Three electron spectrograms: earthward (±11°), antiearthward (±11°), and 50 eV to 10 keV pitch angle energy flux. The middle two panels represent the perpendicular (along satellite path) and the parallel electric fields. Both panels have three electric field signals (each of the colored lines was band-pass filtered differently onboard). Three ion spectrograms: 5 eV to 5 keV pitch angle, antiearthward (±70°), and earthward (±60°) ion flux. The last panel presents the perpendicular electric field. Two DLs are observed, marked by the two vertical lines.

field-aligned electrons at both 0° and 180° and heated ions at 90° (Figure 2). The DC unipolar signature at the vertical line is the DL itself where, ironically, there is no significant wave activity. The ion distribution measured at and just before (above in altitude) the DL indicates that the ions are strongly heated and "plowed" in front of the DL resulting in the strong fluxes at 180° pitch angles (Figure 2). The moving DL turns out to be an efficient process for atmospheric loss [*Hwang et al.*, 2008]. On the low potential side, an earthward-traveling ion beam emerges (accelerated earthward with a significant perpendicular temperature). Upwelling thermal ions at 180° are also recorded. Ions that are heated and mirror well below the DL reach the DL and are reflected. This process results in a modified pressure cooker picture [*Gorney et al.*, 1985; *Hwang et al.*, 2008].

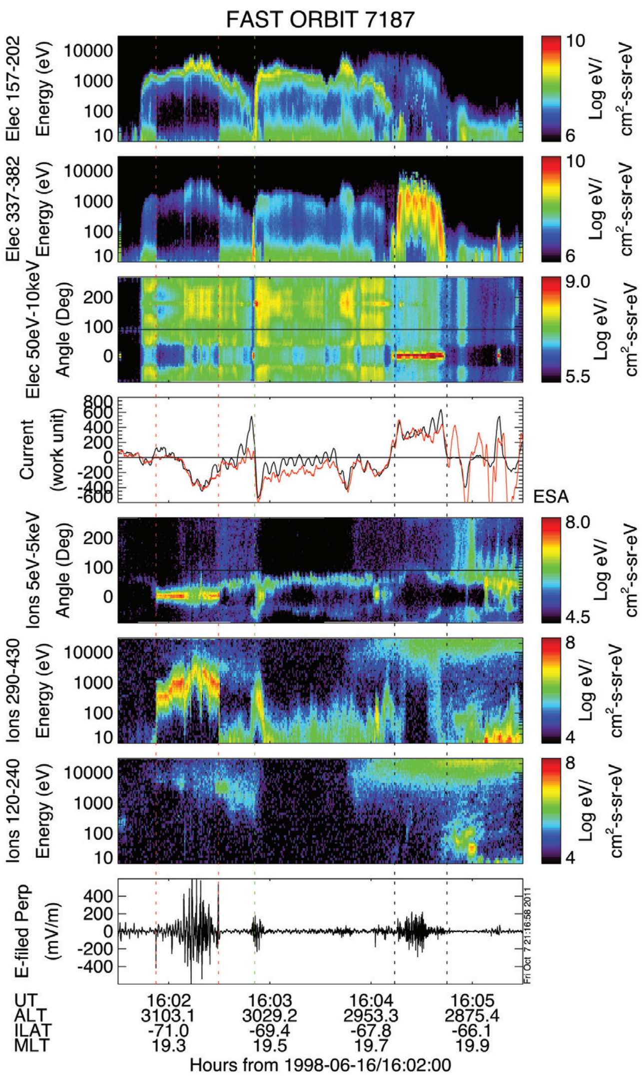

Figure 3. An example of a satellite crossing from the polar cap to the equatorward edge of the auroral oval. The electron and ion spectrograms have the same ranges as in Figure 2. Two inverted-V structures exist between ~16:01:30 and ~16:04:00 UT. The satellite moves into the aurora cavity at the vertical lines where a paired DC electric field can be seen at the boundaries with strong AC waves between the paired electric fields. The electron flux observed from ~16:04:20 to ~16:04:50 UT is during a downward current where the electron flux is modulated as a result of the narrowness of the electron beam and the instrument sector observing this flux.

Strong DLs were also found in the lower boundary (Figure 3) of the upward current region's inverted-V potential structures [*Ergun et al.*, 2002; *Hull et al.*, 2003]. There are some less-definitive observations of more turbulent midcavity DLs [*Ergun et al.*, 2004] of the inverted-V potential. The lower-boundary DLs have been proven to contribute only a smaller fraction (20%–50%) of the net potential associated with upward current region [*Ergun et al.*, 2004]. It has not been demonstrated nor ruled out whether DLs are responsible for the high-altitude acceleration due to lack of high time resolution observations at these altitudes.

The DLs in the upward current region are strong for the ions but weak for the electrons, so contrary to the case in downward current region DLs, the ions control the evolution. The DLs at the lower boundary of the upward current region straddle a strong density gradient. As a result, the DLs are asymmetric [*Main et al.*, 2006]. The DLs at the lower boundary of the inverted-V potential are relatively fixed in altitude as a result of the secondary electrons and upwelling ions. The upwelling ions serve to satisfy the Bohm and Langmuir criteria.

The low-potential side of these DLs (high-altitude side) has the auroral density cavity. Strong wave activity is often associated with an ion-ion two-stream instability since both hydrogen and oxygen ions are strongly accelerated with the same energy into the cavity, which causes them to emerge with differing velocities [*Main et al.*, 2006]. The auroral cavity is also the source region for AKR radiation that can be used to remotely identify inverted-V locations and estimate the altitude location of the main parallel electric field [*Morioka et al.*, 2007].

8. DLS EVERYWHERE (>2010)

The number of observed DLs by the FAST and Polar satellites was limited since the satellites travel primarily perpendicular to the magnetic field, and the vertical scale of DLs is very narrow.

The DL observations by the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission were initially a surprise [*Ergun et al.*, 2009]. The probability of actually observing a DL increased significantly over that of the FAST mission since the THEMIS satellites dwell for long time periods on flux tubes in the magnetotail with strong currents. Furthermore, the magnetotail sound velocity is much higher than that in the low-altitude aurora (1000 km s^{-1} compared to 30 km s^{-1}). The THEMIS DLs were identified by their electric field signal alone since the temporal resolution of the particle instruments on THEMIS mission is too low. The high number of observed DLs in the magnetotail during magnetic disturbances suggests that DLs might be an important process to dissipate the energy in the Earth's magnetotail [*Ergun et al.*, 2009].

DLs also have been inferred in the outer planets. The strong DL creates electron beams. These electron beams lead to electron cyclotron emissions in the upward current regions and VLF saucers in the downward current region. With understanding from the Earth auroral radio signals, the radio signals from Jupiter indicate that DLs are an important process at the magnetosphere of Jupiter [*Hess et al.*, 2009]. Sudden changes in radio spectrograms of "millisecond" bursts at Jupiter have been interpreted as possible DLs [*Hess et al.*, 2009]. Another possible indication of DLs comes from the VLF saucer emission observed at Enceladus in Saturn's magnetosphere [*Gurnett and Pryor*, this volume].

9. WHERE WE ARE TODAY

As of this writing, several distinct types of DLs appear in the data. The DLs in the downward current region of the aurora have strong electron acceleration but appear to have weak ion acceleration, mainly because the ion temperature is much higher than the electron temperature in the vicinity of the DLs. These DLs move antiearthward at the ion-acoustic speed [*Andersson et al.*, 2002] that appears to satisfy the Bohm and Langmuir criteria. For example, the 800 V DL observed in Figure 2 at ~13.5 s is moving at ~30 km s^{-1} antiearthward.

The parallel scale length of these DLs is on the order of 10 Debye lengths, in line with theoretical predictions. The perpendicular scale length has not been directly measured. However, if DLs are the source of VLF saucers, the perpendicular scale size appears to be roughly 100 to 1000 Debye lengths. The motion of the DL dictates that their lifetime is short [*Andersson and Ergun*, 2006; *Marklund et al.*, 2001]. Numerical simulations indicate that if no warm electrons are present, the DLs are disrupted rapidly. However, a warm electron background (often seen in the downward current region of the aurora) can stabilize the DL [*Newman et al.*, 2008]. DLs in the downward current region have been observed as low as ~1500 km [*Elphic et al.*, 2000] and increase in frequency to ~4000 km, the apogee of the FAST satellite and supported by perpendicular electric field observations by the Viking satellite [*Marklund*, 1993]. The net potential associated with the downward current region is often smaller compared to the upward current region, but as Figure 3 demonstrates, sometimes they are equal. Finally, the moving DLs and their associated wave emissions create an interesting scenario for ion heating as discussed in section 7 and, during quiet times, might be an effective process for atmospheric loss, Figure 3.

The other type of DL is associated with upward current region and partly described in section 7. The lower boundary of the inverted-V structure is fairly stationary in altitude as a result of the natural inflow of ions from the ionosphere [*Ergun et al.*, 2002; *Hull et al.*, 2003]. As a result, the DL is at the density gradient between the ionosphere and the aurora cavity. Since the lower boundary DLs in the upward current are controlled by the ions, these DLs are evolving slowly. They are also found to be oblique to the magnetic field. Interestingly, they seem to conform to the "U-shaped" potential structure (Figure 1). Multipoint measurements from the Cluster mission have provided the first glimpse of the evolution of the aurora region and the quasi-static structures in the downward [*Marklund et al.*, 2001] and the upward [*Hull et al.*, 2010] current region.

Other types of unipolar electric fields in the auroral acceleration region have been observed, but well-developed theoretical explanations are lacking. The first is observed unipolar localized parallel electric fields associated with Alfvén waves [*Ergun et al.*, 2005]. In numerical simulations of auroral Alfvén waves, solitary structures have been developed suggesting a DL type of acceleration [*Genot et al.*, 2004; *Mottez*, 2001]. This result is further supported by antiearthward field-aligned ion observations where the ion acceleration process has to be both localized in space and time suggesting that a DL type of acceleration exists in Alfvénic regions. Another puzzle is the closely spaced unipolar electric fields (seen in Figure 2 at ~12.8 s). Such closely spaced unipolar DC electric fields have not been replicated in simulations. So far, any attempt in locating two DLs close to each other has resulted in the destruction of one of them due to the instabilities created by the other (D. L. Newman, private communication, 2003).

10. SUMMARY: UNANSWERED QUESTIONS AND MOVING FORWARD

During the last 70 years, significant progress has been made on DL research, most recently characterizing the strong DLs in the aurora region. However, there are still many questions that need to be answered, both associated with the aurora region and to understand how important strong DLs are for space and astrophysical plasmas.

Some of the outstanding questions for the aurora region are (1) How do quasi-static DLs form? (2) Only a smaller part of potential drop in the upward current region can be explained today by strong DL. Can DLs also explain the rest of the potential drop? (3) Most of the downward current is associated with small perpendicular scale lengths and has short lifetimes. How can the DLs in the downward current sustain the return current? (4) What impact does the slow ion motion and ionospheric convection have on the stability of the DLs? (5) How important are DLs for the atmospheric loss? (6) Can observed parallel electric fields associated with Alfvén waves be explained by DLs? (7) What theories are needed to explain closely spaced unipolar electric fields as observed in Figure 2?

The observation of two different types of DLs in the low-altitude aurora, the observation of DLs in the magnetotail, and the implication of DLs in Jupiter's and Saturn's magnetospheres suggest that the DL is truly a universal process. With significant gaps in our understanding of DL, this area of research will continue to be important.

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