2004
Carl-Gunne Fälthammar
MAGNETIC-FIELD ALIGNED ELECTRIC FIELDS IN COLLISIONLESS SPACE
PLASMAS – A BRIEF REVIEW
*Geofísica Internacional,* april-june, año/vol. 43, número 002
Special Issue (Part B)
Universidad Nacional Autónoma de México
Distrito Federal, México
pp. 225-239

# Magnetic-field aligned electric fields in collisionless space plasmas – a brief review

Carl-Gunne Fälthammar

*Division of Plasma Physics, Alfvén Laboratory, Royal Institute of Technology, S-100 44 Stockholm, Sweden*

**RESUMEN**

Los campos eléctricos alineados a los campos magnéticos juegan un importante papel en la dinámica de los plasmas magnetizados. Ellos permiten el desacoplamiento de los elementos de plasma debido a la violación de la condición de campo congelado, la ruptura del mapeo equipotencial, la eficiente aceleración de partículas cargadas y la liberación rápida de energía magnética. En los plasmas sin colisiones, que ocupan la mayor parte del universo, usualmente se asume que no existen. Sin embargo, una consecuencia muy importante de las mediciones *in situ* ha sido el reconocimiento de que tales campos eléctricos existen en los plasmas sin colisiones a pesar de la ausencia de la colisión friccional. Aunque indicios de su existencia están aún en mediciones en tierra, la prueba final está dada por la abrumadora evidencia de las observaciones *in situ*. Estas incluyen mediciones de algunos rasgos característicos de la función de distribución de las partículas, algunos experimentos y mediciones directas de estos campos eléctricos. Se han identificado algunos mecanismos que apoyan la existencia de estos campos eléctricos. Por ejemplo, la turbulencia, los solitones, los espejos magnéticos, las capas dobles y atrapamiento dinámico. Se ha observado que algunos de estos procesos son importantes en el fenómeno auroral, pero su importancia relativa aún no está bien entendida.

**PALABRAS CLAVE:** Campos magnéticos alineados, campos eléctricos alineados.


**ABSTRACT**

Magnetic-field aligned electric fields play an important role in the dynamics of magnetized plasmas. They allow decoupling of plasma elements by violation of the frozen field condition, breakdown of equipotential mapping, efficient acceleration of charged particles and rapid release of magnetic energy. In the collisionless plasmas that occupy most of the universe they used to be assumed nonexistent. A major consequence of the *in situ* measurements of the space age was the recognition that such electric fields do exist in the collisionless space plasma in spite of the absence of collisional friction. Indications of their existence came even from ground observations, but the final proof rests on the overwhelming evidence accumulated by *in situ* observations. These include observations of a number of characteristic features of particle distribution functions, various active experiments and direct measurements of electric fields. A number of mechanisms that can support magnetic field aligned electric fields have been identified. They include wave turbulence, solitary structures, magnetic mirrors, electric double layers and dynamic trapping. Some of them have been observationally confirmed to be important in the auroral process, but their relative roles are still not well known.

**KEY WORDS:** Magnetic-field aligned, parallel electric fields.

## 1. INTRODUCTION

Before the era of *in situ* measurements in space it was common wisdom that magnetic-field aligned electric fields cannot not exist, because the unimpeded motion of electrons and ions along magnetic field lines would "shortcircuit" them. Accordingly, space plasma was considered to be an essentially ideal magnetohydrodynamic medium. When Hannes Alfvén (1958) proposed that auroral primary electrons might receive their energy by falling through a potential drop above the ionosphere, his proposal was almost universally disregarded as absurd.

Alfvén's bold suggestion had an empirical foundation. For some time a phenomenon called *electric double layer* had been known from laboratory plasma experiments. In such a double layer a strong spatially limited potential drop prevails in a locally collisionless plasma. Although not well understood theoretically, it was a real phenomenon, which caused undesirable current disruptions in technical devices, such as rectifiers for high voltage dc power transmission.

The existence of magnetic-field aligned electric fields in collisionless space plasma is a matter of great importance. (For brevity the term "parallel" will also be used for "magnetic-field aligned".) As described in § 2, such fields allow a violation of the frozen field condition, an efficient acceleration of charged particles and a rapid release of magnetically stored energy.

As soon as relevant *in situ* measurements were made in the space plasma, indications in support of Hannes Alfvén's

idea were found. McIlwain's (1960) observation of auroral primary electrons showed a high degree of collimation, followed by observations by Albert (1967) and Evans (1968) of "monoenergetic" electron fluxes. These early observations have been supplemented by a large body of data, and the observational evidence of magnetic-field aligned electric fields in the collisionless plasma of the auroral acceleration region is now overwhelming (§ 3).

A key question is how the momentum imparted to the charged particles by the parallel electric field can be balanced in the absence of collisional friction (§ 4). Depending on what mechanism is responsible for maintaining this momentum balance, the parallel electric fields can have very different characteristics (§§ 5-7).

## 2. SIGNIFICANCE

The existence of non-vanishing magnetic-field aligned components of electric fields has important consequences, because such fields allow (1) violation of the frozen field condition, (2) efficient acceleration of charged particles, and (3) rapid release of magnetically stored energy.

*Violation of the frozen field condition*

The concept of *frozen-in magnetic field lines* was discovered by Hannes Alfvén along with the waves that bear his name. This well-known concept greatly simplifies physical reasoning about plasma physical problems. It is, however, based on crucial assumptions that are not always valid in a real plasma, especially in space. Therefore, especially in his later years, Hannes Alfvén vigorously warned against unjustified use of the concept.

In a rigorous definition, a state of frozen-in magnetic field lines is one where any two plasma elements that are at one instant on a common magnetic field line will be on a common magnetic field line at any other instant (Figure 1). When the frozen condition in this sense holds plasma elements can be used to "label" magnetic field lines and then also to indirectly define their "motion".

As illustrated by Alfvén and Fälthammar (1963, § 5.4.1), the frozen field condition can be violated if the electric field has a component along the magnetic field. For such "unfreezing" or "cutting of magnetic field lines" to occur, the necessary and sufficient condition can be written

$$curl \; [(\textbf{\textit{E}} \bullet \textbf{\textit{B}}) \; \textbf{\textit{B}}/\textbf{\textit{B}}^2] \neq 0.$$

For a rigorous mathematical treatment, see *e.g.* Newcomb (1958).

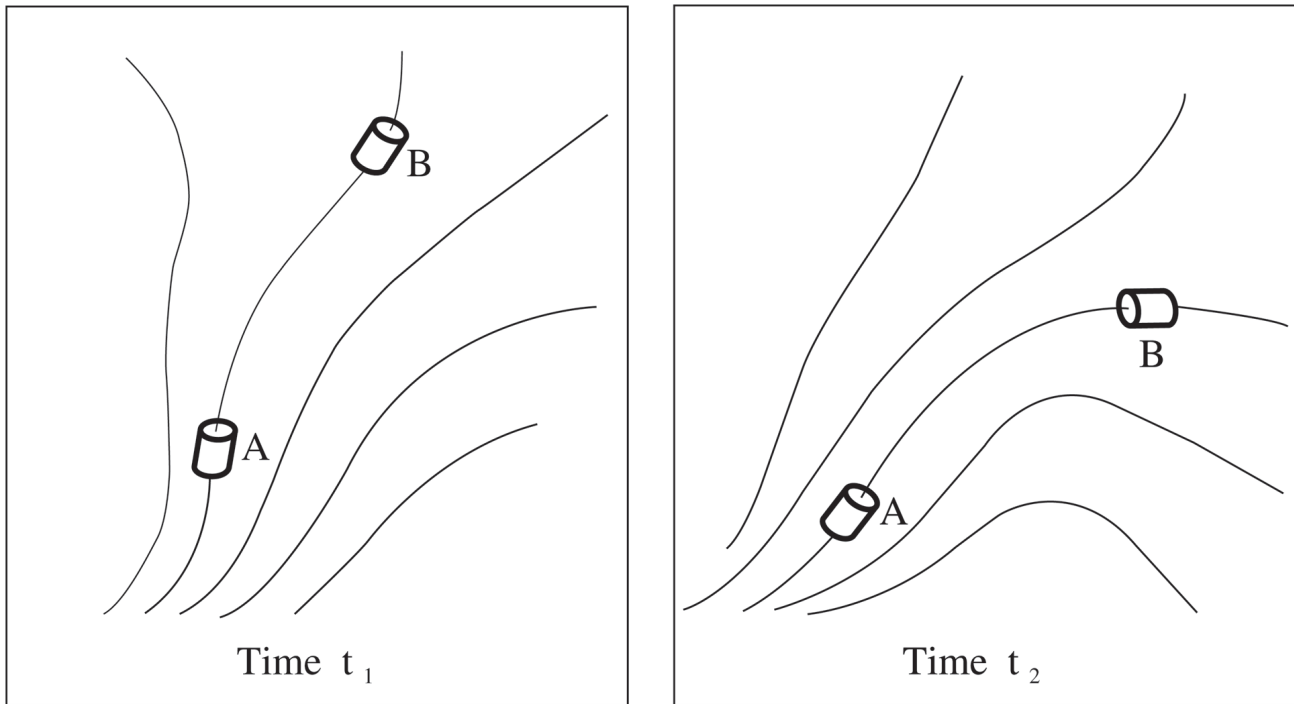*Violation of the frozen field condition has a twofold significance:*



Fig. 1. Frozen magnetic field. Two elements of plasma, such as A and B, that are at any one time, $t_1$, on a common magnetic field line will be on a common magnetic field line at any other time, $t_2$.

(1) the "mapping" of electric fields along magnetic field lines breaks down, and

(2) plasma elements which are at one time in a common magnetic field line may be on different field lines at another time (Figure 2).

This means for example that the electric field pattern, and the corresponding convection pattern, in the magnetosphere need not be magnetically conjugate with that in the ionosphere. Such mismatch can be expected on auroral field lines, where parallel electric fields are known to be present.

It also means that change of connectivity is possible not only at magnetic x-points (as in ordinary reconnection) but also within regions of non-vanishing magnetic field (as in Figure 2). This process was studied by Schindler *et al*. (1988) and Hesse and Schindler (1988) who proposed that the term reconnection should not be limited to the ordinary (Zero-*B*) reconnection, but equally well to Finite-*B* reconnection. This has been further elaborated by for example Birn *et al*. (1997).

*Acceleration of charged particles*

Acceleration of charged particles can only be achieved by electric fields, because the force from any magnetic field is transverse to the velocity vector and leaves the particle's energy intact. There are two main ways in which the charged particle acceleration can take place:

(1) stochastic (multi-step) acceleration, where each particle performs a random walk in energy

(2) direct (one-step) acceleration in a (quasi)static electric field.

In stochastic acceleration the net energization accumulates gradually as a result of many positive and negative energy steps. In contrast, direct acceleration by free fall through a dc electric potential drop is the most efficient possible way for a charged particle to gain energy.

*Rapid release of magnetically stored energy*

Energy stored in a magnetic field is by necessity associated with an electric current system with an inductance. If somewhere in the electric circuit there is established an electric field with the electric vector in the same direction as the current, the current will for some time continue to flow, driven by the inductance, and the dissipation of power in the region of the potential drop can drain the magnetic energy with great efficiency. This mechanism has been invoked in astrophysical applications, and the phenomenon is known from laboratory experiments with "exploding" electric double layers .
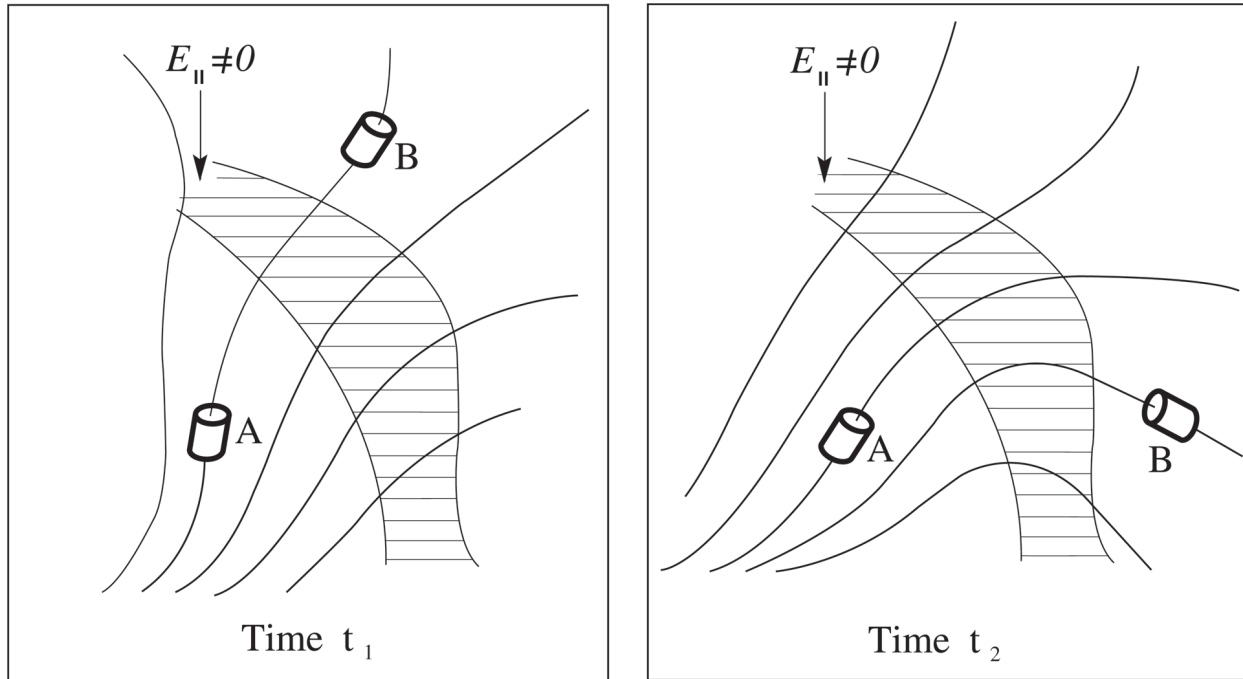


Fig. 2. Violation of the frozen field condition. Elements A and B that are at time $t_1$ on a common magnetic field line will be on different magnetic field lines at another time, $t_2$. This is possible if between A and B there is a region where there is a magnetic-field aligned electric field with non-vanishing curl.

## 3. OBSERVATIONAL EVIDENCE

The existence of parallel electric fields in space plasma gradually achieved general recognition as a result of massive observational evidence of many kinds. They include:

*Ground based observations*

Already long ago it was argued by Carlqvist and Boström (1970) that the motion of auroral curls indicated different transverse electric fields at different altitudes, which in turn would imply that a magnetic-field aligned electric field must exist in some intermediate region. This is an example of the Finite-*B* reconnection mentioned in § 2.

Using the sophisticated observations made possible by the EISCAT radar Olsson *et al*. (1996) introduced a new technique that allows determining the magnetic-field aligned conductance from groundbased observations alone.

*Features of observed natural particle populations*

*In situ* observations of natural particle populations have revealed a number of features indicative of direct acceleration in a parallel electric field.

(1) *Precipitating electron distributions* with narrow energy range and high angular collimation, indicating an *upward* directed potential drop *above* the observer. Sometimes the velocity distribution function looks like a Maxwellian after falling through an electric potential. In other cases the velocity distribution is thoroughly modified by wave particle interaction.

(2) *Upgoing ion beams* and *"elevated" ion conics* carry information about an *upward* directed electric potential drop *below* the satellite. Sometimes the bulk energy does not reflect the entire potential drop, because there has also been a certain degree of thermalization.

(3) *Widened loss cone* in the electron velocity distribution is another signature of *upward* potential drops *below* the satellite.

(4) *Upgoing electron beams* reveal the presence of *downward* directed electric fields below the satellite.

Comparisons have shown that the electric potential estimated from different features are in good mutual agreement (e.g. Reiff *et al*., 1988).

*Active experiments*

Some conspicuous evidence of magnetic-field aligned electric fields has come from experiments where artificially created particle populations have been injected into auroral flux tubes. Among experiments of this kind the most spectacular is probably the famous Porcupine experiment where Haerendel *et al*. (1976) observed the acceleration of a cloud of barium ions coincident with the onset of an aurora in the same magnetic flux tube. The velocity increase corresponded to a voltage drop of 7.4 kV, and occurred at an altitude of 7500 km.

*Measured electric fields*

Strong *transverse* electric fields, which are measured at high altitude but absent in the ionosphere below imply the existence of a parallel electric field somewhere in the intervening altitude range (cf. § 2.).

Direct measurement of the parallel component of the electric field is, with existing techniques, not possible for a smoothly distributed field of moderate strength (of the order of mV/m), but lumped electric fields of double layer type have been observed (cf. § 7).

## 4. MOMENTUM BALANCE

For a non vanishing magnetic-field aligned electric field to exist other than as a brief transient, the momentum that this field continually imparts to the charged particles must be balanced. Depending on how this momentum balance is achieved, a number of different types of magnetic-field aligned electric fields are possible, each with its own characteristics.

*(1) Forces from ac electric fields*

The dc electric force may be balanced by an equal and opposite net force from the ac electric fields associated with *waves* or with *solitary structures*. The former is the case in anomalous resistivity, and the second has been invoked to explain parallel electric fields observed in the downward current region of the auroral circuit. Both will be discussed in § 5.

*(2) Forces from the dc magnetic field*

A converging dc magnetic field will give rise to the *magnetic mirror effect* (§ 6), which on high latitude magnetic field lines in the Earth's magnetosphere is sufficient to support magnetic–field aligned potential drops of several kV.

*(3) Inertial forces*

When no other force is available to balance the force from the dc electric field, the momentum has to be absorbed by the inertia of the charge carriers themselves. Early examples of this are the *electric double* layer and *the collisionless thermoelectric effect*. A more recent one which

has been observed in active experiments is *dynamic trapping*. Inertia-supported electric fields will be discussed in § 7.

## 5. ELECTRIC FIELDS FROM WAVES AND SOLITARY STRUCTURES

*Anomalous resistivity*

In the search for mechanisms that could support parallel electric fields, one of the first to be identified was *anomalous resistivity*, envisaged as a state of instability-driven wave turbulence, where the ac electric fields of the waves are strong enough to greatly impede the motion of current carrying electrons. An early review of its application to the Earth's ionosphere was given by Papadopoulos (1977).

As shown by Block (1984), anomalous resistivity supporting kV potential drops in the presence of auroral field aligned currents would lead to an extremely fast heating of the local plasma. Also, Cornwall and Chiu (1982) noted that anomalous resistivity is far too dissipative. The interest in applying anomalous resistivity as a means of supporting parallel electric field in the auroral acceleration region also diminished because the magnetic mirror effect (§ 7) was very successful in explaining those observations (Yeh and Hill, 1981). The role of anomalous resistivity for sustaining parallel electric fields in the magnetosphere at all was questioned by Coroniti (1985). Although anomalous resistivity may play a role in the context of reconnection (see *e.g.* Hesse *et al.* 1999) and tail current disruption (Perraut *et al.*, 2000, Pritchett and Coroniti, 2002), its role, if any, in sustaining dc magnetic-field aligned electric fields still remains to be determined.

*Solitary structures*

One of the discoveries of the FAST satellite was the occurrence of large numbers of *solitary potential structures* in the downward current region of the mid altitude auroral zone (Ergun *et al.*, 1998a,b, Ergun, 1999). These structures (Figure 3) were observed to have large amplitudes, up to 2 500 mV/m and (positive) potentials of the order of 100 V. They travel anti-Earthward at a speed of the order of 4500 km/s. They occur in or near regions of magnetic-field aligned electric fields. Ergun *et al.* (1998a,b) proposed that these solitary structures play a key role in supporting the observed magnetic-field aligned electric fields.

## 6. MAGNETIC MIRROR EFFECT

*Differential anisotropy*

As first demonstrated by Alfvén and Fälthammar (1963), a magnetic mirror can support a magnetic-field aligned electric field in a collisionless plasma if the positive and negative particles have a *differential anisotropy, i.e.* if the distribution function integrated over velocity has a different angular distribution for positive and negative particles. As an example of how differential anisotropy can be generated, they considered the case where ions trapped near the equatorial plane are neutralized by electrons pulled out along magnetic field lines from the upper ionosphere. More general cases of this mechanism have been analysed by Persson (1963, 1966), Whipple (1977) and Ponyavin *et al.* (1977).

However, it has turned out that almost any way of injecting a plasma into a mirror configuration will tend to produce differential anisotropy. For example, Serizawa and Sato (1984) proposed injection of a cloud of plasma into the converging geomagnetic field of the auroral acceleration region as a way to generate the required differential anisotropy. As in this case ions and electrons have the same bulk velocity but different thermal velocities, the differential anisotropy is automatically established (Figure 4). This mechanism was further discussed by Washimi and Katanuma (1986). It was studied in laboratory experiments by Sato *et al.* (1988) and in numerical simulations by Schriver and Ashour-Abdalla (1993) and Ishiguro *et al.* (1995). Most interestingly, Le Contel (1999) showed by means of a self consistent simulation that basically any unsteady plasma transport in the presence of a magnetic mirror field will lead to differential anisotropy and magnetic-field aligned electric fields. The particular case of the substorm growth phase was studied by Le Contel *et al.* (2000).
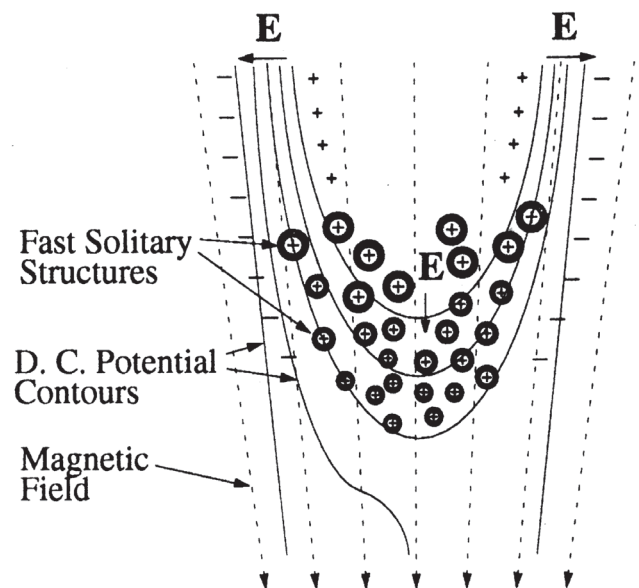


Fig. 3. Fast-moving solitary structures observed with the FAST satellite have been proposed to play a key role in supporting the magnetic-field aligned electric field that are also observed. From Ergun *et al.* (1998b).
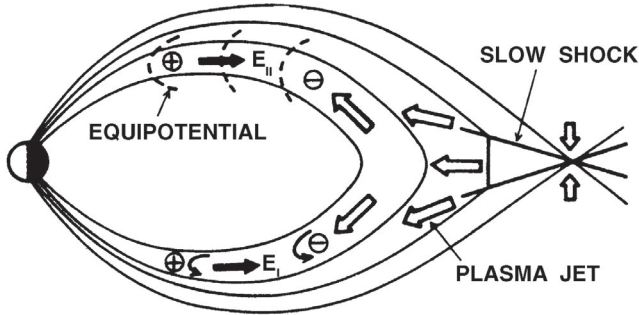
Fig. 4. Generation of magnetic-field aligned electric field by plasma jetting into the geomagnetic mirror field according to Serizawa and Sato (1984).

*Current out of magnetic mirror*

In the auroral acceleration region an electric current flows out of a magnetic mirror and is carried mostly by elec-

trons flowing in through the mirror and creating the aurora. In the absence of a magnetic-field aligned potential drop the electron current is limited to what can be carried by the electrons in the loss cone. As the mirror ratio from the magnetosphere to the ionosphere is large, the loss cone is very narrow. For typical parameters applying to auroral flux tubes the current carried by loss cone electrons is of the order of $1\mu A/m^2$ or less. For any larger current density to be carried, a magnetic-field aligned potential drop has to be applied. The effect of the potential drop is to widen the loss cone into a loss hyperboloid (Figure 6). As the voltage is increased, the loss hyperboloid widens until, asymptotically, it approaches the entire downward directed half of velocity space. The current is then saturated, and can not increase further whatever voltage is applied. For typical auroral parameters this saturation current is of the order of hundreds of $\mu A/m^2$ or more and is reached at potentials of the order of 10 kV.

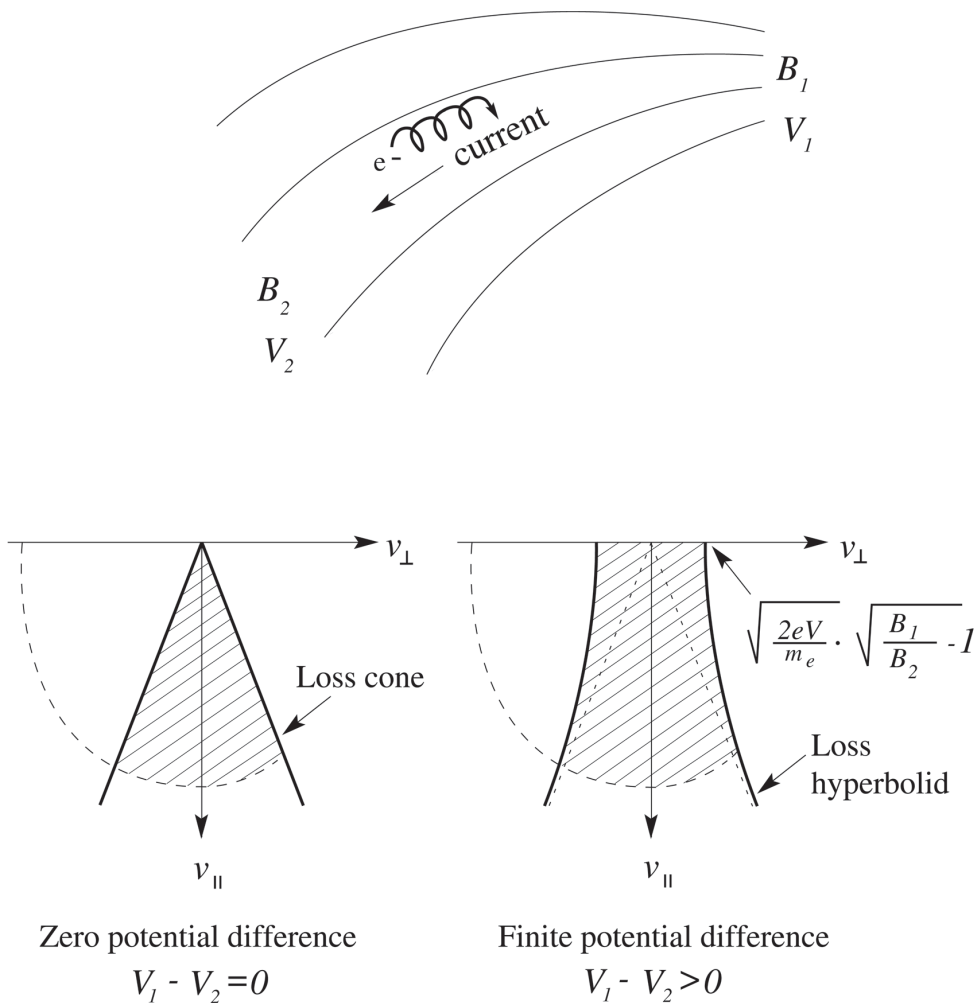A quantitative expression for the relation between ap-



Fig. 5. Current out of a magnetic mirror. The current carrying electrons are restrained by the magnetic mirror. In the absence of a potential difference only the electrons in the loss cone can go all the way and carry a current. A magnetic-field aligned electric field pointing out of the mirror will widen the loss cone into a loss hyperboloid and correspondingly increase the current.

plied parallel potential drop and the corresponding current density was first derived by Knight (1973), and also analysed by Lemaire and Scherer (1974), for the case of Maxwellian distributed electrons in the source plasma. Over a rather wide range of current and voltage this current-voltage relation is linear. For parameters typical of auroral flux tubes, the linear region extends over nearly three powers of 10 and covers the range of typical auroral currents and voltages (Figure 6), and its slope, which represents the *conductance* of the auroral flux tube, is $3.10^{-9}$ S (Fälthammar, 1978). Using more practical units we can write this as 3 ($\mu A/m^2$)/kV, i.e. an electron current density of 3 $\mu A/m^2$ for every kV applied.

The current-voltage relation was later generalized by several authors (Friedman and Lemaire, 1980, Chiu *et al.*, 1981, Janhunen and Olsson, 1998 and references therein). For very low values of the voltage, ionospheric electrons and ions must be taken into account. This low voltage case was analysed by Pierrard (1996).

The first observational confirmation of the linear current-voltage relation by Lundin and Sandahl (1978) was followed by numerous others (Lyons *et al.*, 1979, Menietti and Burch, 1981, Weimer *et al.*, 1987, Lu *et al.*, 1991, Haerendel *et al.*, 1994, Sakanoi *et al.*, 1995, Olsson *et al.*, 1996, 1998, Olsson and Janhunen, 1998). Olsson *et al.* (1996) developed a method of determining the conductance value from ground based observations alone, using an inversion technique to calculate the flux-energy spectra and estimating source densities, thermal energies and potential drops by fitting accelerated Maxwellian distributions. Using this tool Olsson *et al.* (1996) determined the conductance in auroral breakups and westward travelling surges. They found that the linear relation (constant conductance) can hold even at very high

voltages (20 kV), and that the conductance values can be as low as several times 10-11 S (0.01 ($\mu A/m^2$)/kV). Very low conductance values are not surprising, because the theoretical formulas quoted above are based on the assumption of an isotropic source plasma. If the replenishment of the loss cone of the source plasma is insufficient, the current density at given voltage will be reduced.

Menietti and Burch (1981) found excellent agreement even with a higher approximation to the full current-voltage relation and Brüning *et al.* (1990) reported observation of saturation current. Sakanoi *et al.* (1995) showed that the conductance is 5-10 times larger at the edges of inverted V regions that in the in the middle, suggesting that nonadiabatic pitch angle scattering also plays a role.

Whereas the above-mentioned theories provide a relation between the current density and the height integrated potential drop, the altitude distribution of the potential has remained an open question. Recently Ergun *et al.* (2000) studied this problem using Vlasov simulation guided by observations from the FAST satellite. They not only confirm that the current-voltage relation closely follows the Knight relation, but they conclude that the altitude distribution of the potential drop is characterized by three distinct regions separated by transition layers. The low altitude region, dominated by ionspheric plasma, is bounded by a transition suggestive of an electric double layer (cf. § 7) with a narrow potential drop being located within less than one grid step (128 km). The high altitude region, populated by plasma sheet plasma, is limited by another abrupt potential drop, also in less than a grid step. The intermediate region is dominated by ionospheric ions and magnetospheric electrons, which are forced to quasineutrality by a smoothly varying potential. These general features were confirmed observationally by Mozer and Hull (2001) in an extensive study using data from the Polar satellite.

## 7. CHARGE CARRIER INERTIA

*Electric double layers*

The first identified category of inertia-supported parallel electric fields was the *electric double layer*. An electric double layer is a space charge structure with a thickness of the order of $C(eV/kT_e)^{1/2}\lambda_D$, where $\lambda_D$ is the Debye length, $V$ is the voltage drop in the double layer, $T_e$ is the electron temperature and $C$ is a factor of the order of 10.

*Current carrying* electric double layers are of two kinds, *weak* double layers with potential drops comparable to the voltage equivalent of the ambient electron thermal energy ($V \leq kT_e/e$), and *strong* double layers with potentials much greater than that ($V \gg kT_e/e$). Electric double layers with
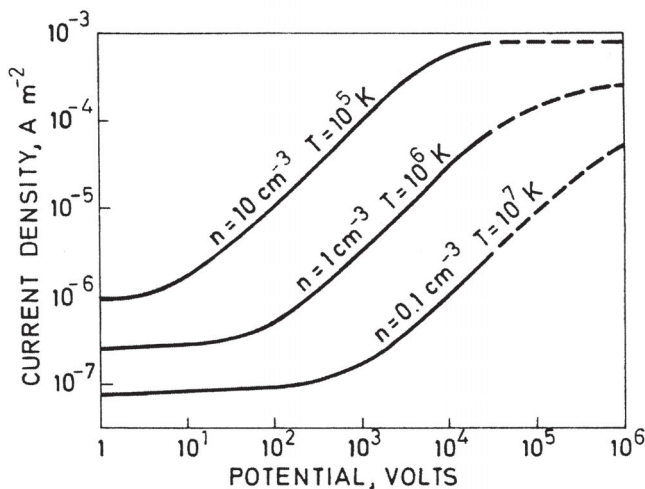
Fig. 6. Relation between current density (at the ionospheric level) and applied potential for parameters characteristic of auroral flux tubes (Fälthammar 1978).

*eV/kT$_e$* as large as 2000 have been observed in the laboratory (Sato, 1982). An example is shown in Figure 7.

Weak electric double layers with *no net current* (also called wall sheaths) are well known from laboratory plasma experiments, where their function is to equalise the flux of positive and negative charges to the wall surrounding the plasma. Interestingly enough electric double layers of this nature and a corresponding function have recently been found in space as reported by Mozer and Hull (2001), who found field strengths of hundreds of mV/m in such structures.

*Strong double layers*

An important feature of electric double layers in space is that the energy imparted to electrons and ions that fall through them is not deposited locally. For example, auroral primary electrons can gain energy by falling through a double layer at high altitude and deposit that energy in the dense ionosphere thousands of kilometers below. Therefore there is no problem of excessive local heating like that in anomalous resistivity.

Because of the small spatial extent of strong electric double layers, measuring them directly is difficult although not impossible (Boehm and Mozer, 1981, Mozer and Kletzing, 1998, Ergun *et al*., 2001a, Mozer and Hull, 2001). In a recent study using data from the Polar satellite, Mozer and Hull (2001) have confirmed observationally that the low altitude transition layer predicted by Ergun *et al*. (2000) exists and has a character and function somewhat similar to that of the wall sheath in a laboratory plasma.

Recently Ergun *et al*. (2001b) concluded that large electric double layers can account for the parallel electric field



Fig. 7. Contours of constant plasma potential in a steady state electric double layer observed in the laboratory (Sato 1982).

observed in the downward current region. By means of a Vlasov simulation of the auroral arcs that are observed downstream of Io's magnetic footprint in Jupiter's magnetosphere Su *et al*., (2001) found localized potential drops (much smaller than the grid size) at 2-3 Jupiter radii.

*Weak double layers*

*Weak* electric double layers (as well as soliton-like structures with zero net potential drop) occur profusely in regions where upward flowing ions are observed. They move rapidly upward along the magnetic field (from 5 km/s to 50 km/s or more). First detected with the S3-3 satellite (Temerin *et al*., 1982) they have been studied in detail by many authors, see *e.g.* Eriksson *et al*. (1997) and references therein. Although each of the weak double layers has a potential drop of less than 1 V, they are so numerous that they might conceivably account for a total potential drop of several kV. The clear correlation between occurrence of ion beams and of weak double layers may or may not mean that the ions are accelerated by the double layers. It may also be that ion beams accelerated by some other mechanism are the cause of the double layers, or that both are independent consequences of the same physical process. So far, the role, if any, that the weak electric double layers play in auroral region particle acceleration remains an open question (Mälkki and Lundin, 1994).

*Electric double layers in astrophysics*

Electric double layers have also been invoked in astrophysical applications. Alfvén (1978) suggested that electric double layers are responsible for the enormous energy release observed in extragalactic radio sources. In this case the central galaxy was assumed to act as a unipolar generator driving a gigantic current system, in which the double layers were formed. This idea was elaborated by Borovsky (1986), whose model combines anomalous resistivity and electric double layers "in symbiosis". Beam driven waves on both sides of the double layer reduce the mobility of charge carriers (anomalous resistivity) and hold open a density cavity in which the double layer resides. In the double layer "electrical energy is dissipated with 100 % efficiency into high energy particles, creating conditions optimal for the collective emission of polarized radio waves." A comprehensive review of the physics of the electric double layer and its astrophysical applications was given by Raadu (1989).

Carlqvist (1995) analysed electric double layers in multicomponent plasmas and included relativistic effects. One of his results was that the relativistic electric double layer is a selective accelerator. This means that the particles accelerated by the double layer in general have different abundance ratios than the source plasma. Carlqvist suggested that this
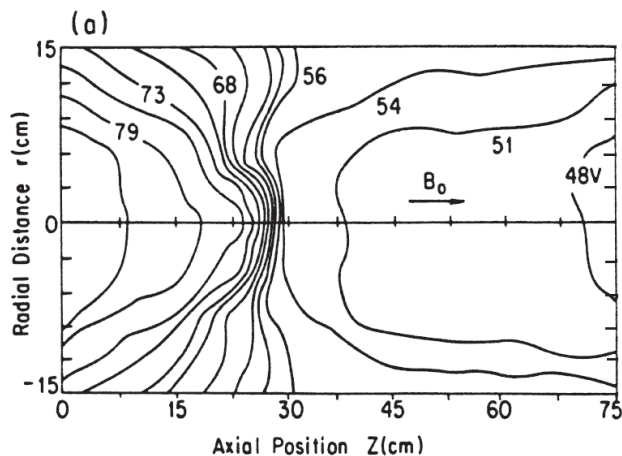
may provide a means of detecting the presence of electric double layers in cosmical plasmas.

*Collisionless thermoelectric effect*

Hultqvist (1971) showed that at the interface between the hot plasmasheet plasma and the cool ionospheric plasma large parallel electric potentials may be created. According to Hultqvist the basic cause is the existence of a higher flux of electrons from the hot plasma into the cold than in the opposite direction. This unbalance of charge flux automatically creates a potential barrier that balances the fluxes (Figure 8). The resultant voltage depends rather sensitively on the height distribution of temperatures and densities but voltages in the kilovolt range were deemed to be possible. In an recent comprehensive study of data from the Freja satellite Hultqvist (2002) finds strong indications that this mechanism plays a role for sustaining the downward directed parallel electric fields in the downward current region of the auroral current circuit.

Although the collisionless thermoelectric effect was proposed for application to the auroral region, observations reported by Singh (1993) indicate that it may be important also at lower latitudes. Possibly related phenomena have also been observed in the laboratory (Hatekayama *et al.*, 1983, Inutake *et al.*, 1985, Hairapetian and Stenzel, 1990) and in numerical simulation (Swift, 1992).

*Scarcity of charge carriers*

The electron density a thousand km above auroral arcs is often well below $10^6$ m$^{-3}$. In order to carry electron current densities that are common in auroral arcs, electrons of that low density must be accelerated to a very high velocity. This means, as described by Rönnmark (1999), that if a magnetospheric dynamo imposes a current of a few µA/m$^2$ to and

from the ionosphere, kilovolt potentials will automatically be sustained simply due to the finite inertia of the electrons. This analysis was supplemented by a two dimensional simulation (Rönnmark and Hamrin, 2000) and further elaborated in a recent paper by Rönnmark (2002), who finds a current-voltage relation, different from the Knight relation. It still remains to test this relation observationally. Rönnmark's analysis has been questioned by Boström (2002).

In the downward current region of the auroral circuit, the ionospheric electrons constitute an abundant supply of charge carriers. It therefore seemed an unlikely place to find parallel electric fields. But following the discoveries with Freja (Marklund *et al.*, 1997) and FAST (Carlson *et al.*, 1998) of extremely strong diverging electric fields (of the order of 1000 mV/m) and upward directed extremely narrow electron beams it was generally accepted that large downward directed electric potential drops are common in the downward current region. Sheets of downward field aligned currents in this region have been linked by Marklund *et al.* (1994, 1997) to the phenomenon of *black aurora*, which has been known for a long time but not understood until now. Recent discoveries made with the Cluster satellites (Marklund *et al.*, 2001) have demonstrated the role of the downward current region as an important element of the auroral current system, and revealed an intimate interplay between the auroral current and the ionospheric electron supply.

Temerin and Carlson (1998) concluded that even in the downward current region where the ionosphere provides a abundant supply of electrons to carry the current, large potential drops may be supported by electron inertia. The reason is that quasineutrality constrains the spatial density of the current carrying electrons to be equal to the background ion density, which at high altitudes can be very low. In their example (ion density of the order of $10^6$ m$^{-3}$ and 1.6
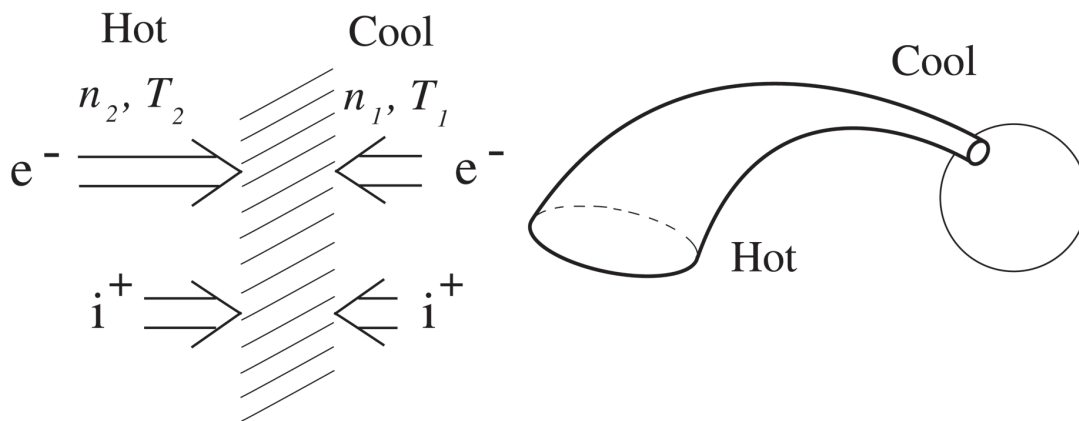


Fig. 8. Collisionless thermoelectric effect proposed by Hultqvist (1971, 2002). At the boundary between hot and cool plasma, the random thermal currents do not match, and a potential barrier is established so as to adjust the net current to zero, or to whatever finite value is imposed by the external circuit,

µA/m² current density at ionospheric level), the potential drop must be at least 283 V, but can, depending on the density distribution be substantially larger. As pointed out by Temerin and Carlson, the model used may not be stable and the time dependent response of the altitude distribution of density and electric field must be taken into account.

*Dynamic trapping*

Still another inertia-based mechanism that can support magnetic-field aligned electric fields is dynamic trapping (Bohm *et al.*, 1990). This  a mechanism that brings about neutralization of charge unbalances in a collisionless plasma and is therefore fundamental to the dynamics of such plasmas. Under certain conditions it can also support parallel electric fields. The essence of the mechanism can be described as follows.

Suppose that in a region of a collisionless plasma an excess positive charge is introduced. (This is a situation that occurs in certain active space experiments, but also in natural space plasma). The excess positive charge will create a positive potential, which attracts neutralizing electrons from the ambient plasma, pulling them in along magnetic field lines. Unlike what would happen in a collision dominated plasma, the electrons will not stop in the high potential region. Instead, as they enter the region of excess positive charge, they speed up along the magnetic field until they reach the potential maximum, then slow down as they continue beyond it. If the potential were constant in time, the electrons would leave the region with the same speed at which they arrived.

In reality, the excess charge and the positive potential will be established on a finite time scale, growing from zero up to a finite time dependent value. In this case, too, electrons will speed up and slow down but by the time they reach the far end of the region the potential has increased. Therefore the slowest electrons cannot leave but get trapped. As the potential keeps growing, the trapped electrons oscillate with a decreasing spatial amplitude. Each trapped electron has maximum speed, and so makes the smallest contribution to charge density, at the peak of the positive potential. If the size of the region is much larger than the Debye length, the potential will grow large enough to trap a number of electrons that very nearly matches the number of excess ions. Also within the region  the potential will have to adjust itself so as to maintain quasineutrality by enforcing a local balance between the density of excess ions and the combined density of trapped and free electrons. This will require a residual positive potential of finite value and appropriate spatial distribution. Figure 9 shows the spatial distribution of particles and electric potential in a numerical simulation by Bohm *et al.* (1990).
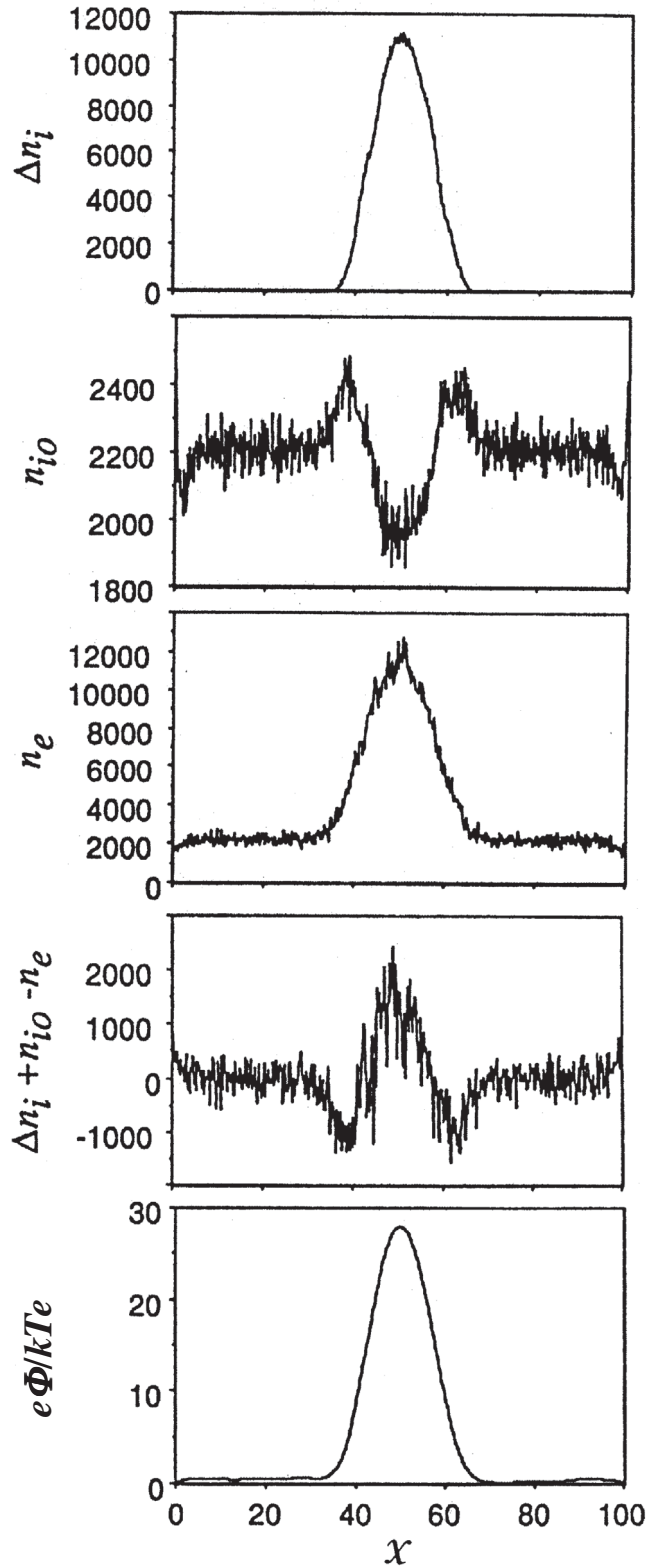


Fig. 9. Numerically simulated dynamic trapping. From top to bottom: The injected ion density, the ambient ion density, the electron density, the net charge density, and the normalized potential. $T_e$ is the electron temperature of the ambient plasma (Brenning *et al.*, 1990).

Unlike what is true for a collisional plasma the potential of the magnetic-field aligned electric field can, if certain conditions are satisfied, exceed the voltage equivalent of the thermal electron energy (of the ambient plasma) by a factor much larger than unity (Figure 10). Bohm *et al.* (1990) used a simple analytical model to estimate the magnitude of this factor and found it to be given by the square of the density ratio between trapped and ambient electrons. The authors also used a numerical simulation, and found a very close agreement with the analytical result. At small values of the density ratio, the relation takes the same mathematical form as the Boltzmann relation. As shown by Brenning *et al.* (1990) dynamic trapping justifies extension of the Boltzmann equation to small positive potentials.

The relation derived by Bohm *et al.* (1990) was used by Bohm *et al.* (1992) to successfully explain parallel electric potential drops measured in the famous Porcupine rocket project (Haerendel and Sagdeev, 1981, Häusler *et al.*, 1986). In this project a subpayload emitted a high energy beam of xenon ions transverse to its axis of rotation. As the beam swept past the main payload, electric potential drops were measured which implied magnetic-field aligned electric field components. How these were sustained could not be explained by any mechanism known until then, but predictions based on the mechanism of dynamic trapping showed good agreement with the measured potential drop.

## 8. CONCLUDING REMARKS

On theoretical grounds, magnetic-field aligned electric fields used to be considered impossible, and space plasma was believed to obey the idealized magnetohydrodynamics that assumes their absence. Only when *in situ* measurements in the space plasma became possible, was this serious error exposed. We now know that essential parts of space plasma dynamics, and in particular auroral acceleration, depend on

magnetic-field aligned electric fields. This illustrates the importance of theory and experiment going hand in hand. Because of the complexity of magnetized plasma, theoretical models can too easily go astray if not checked against empirical data. Conversely, theory is needed to go from the empirical data to a genuine understanding of the physics involved. In auroral physics great progress has been achieved, but much remains still to be done both experimentally and theoretically. We still need a better empirical knowledge of the distribution in space and time of the magnetic-field aligned electric fields, and we need to understand the relative roles of the various mechanisms that make them possible.

## BIBLIOGRAPHY

ALBERT, R. D., 1963. Nearly Monoenergetic Electron Fluxes Detected During a Visible Aurora. *Phys. Rev. Lett., 18,* 369-372.

ALFVÉN H., 1958. On the Theory of Magnetic Storms and Aurorae. *Tellus 2, 10,* 104-116.

ALFVÉN, H.,1978. Double Radio Sources and the New Approach to Cosmical Plasma Physics. *Astrophys. Space Sci., 54,* 279-292.

ALFVÉN, H. and C.-G. FÄLTHAMMAR, 1963. Cosmical Electrodynamics, Clarendon Press, Oxford.

BIRN, J., M. HESSE and K. SCHINDLER, 1997. Theory of Magnetic Reconnection in Three Dimensions. *Adv. Space Res., 19,* 1763-1771.

BLOCK, L. P., 1984. Three-Dimensional Potential Structure Associated with Birkeland Currents, Magnetospheric Currents, AGU Geophysical Monograph 28, Ed. T. Potemra (Proc. Chapman Conf. on Magnetospheric Current Systems, Irvington, Virginia, April 5-8, 1983), 28, 315-324.

BOEHM, M. H. and F. S. MOZER, 1981. An S3-3 Search for Confined Regions of Large Parallel Electric Fields. *Geophys. Res. Lett., 8,* 607-610.

BOHM, M., N. BRENNING and C.-G. FÄLTHAMMAR, 1990. Dynamic Trapping: Neutralization of Positive Space Charge in a Collisionless Magnetized Plasma. *Phys. Rev. Lett., 65, 7,* 859.

BOHM, M., N. BRENNING and C.-G. FÄLTHAMMAR, 1992. Dynamic Trapping of Electrons in the Porcupine
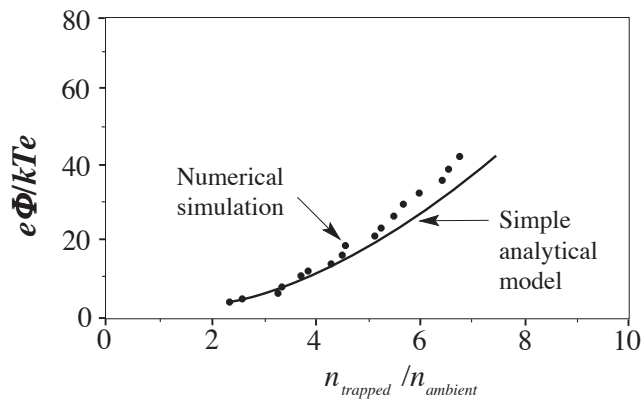
Fig. 10. Normalized potential as a function of the relative densities of injected and ambient ions. Even for moderate values of this ratio the voltage is tens of times larger than kTe/e. (Brenning *et al.* 1990)

Ionospheric Io Beam Experiment. *Adv. Space Research, 12, 12,* 9.

BOROVSKY, J. E., 1986. Parallel Electric Fields in Extragalactic Jets: Double Layers and Anomalous Resistivity in Symbiotic Relationships. *Astrophys. J., 306,* 451-465.

BOSTRÖM, R., 2002. Kinetic and Space Charge Control of Current Flow and Voltage Drops Along Magnetic Flux Tubes. I. Kinetic Effects, Submitted to *J. Geophys. Res.*

BRENNING, N., C.-G. FÄLTHAMMAR, and M. BOHM, 1990. An Extension of the Boltzmann Relation to Collisionless Magnetized Plasma, Report TRITA-EPP-90-08, The Royal Institute of Technology, Stockholm.

BRÜNING, K., L. P. BLOCK, G. T. MARKLUND, L. ELIASSON, R. POTTELETTE, J. S. MURPHREE, T. A. POTEMRA and S. PERRAUT, 1990. Viking Observations Above a Postnoon Aurora. *J. Geophys. Res., 95,* 6039-6049.

CARLQVIST, P. and R. BOSTRÖM, 1970. Space-Charge Regions above the Aurora. *J. Geophys. Res, 75,* 7140.

CARLQVIST, P., 1995. Multicomponent Double Layers and Selective Acceleration of Charged Particles. *J. Geophys. Res., 100,* 205-212.

CARLSON, C., W., J. P. MCFADDEN, R. E. ERGUN, M. TEMERIN, W. PERIA, F. S. MOZER, D. M. KLUMPAR, E. G. SHELLEY, W. K. PETERSON, E. MOEBIUS, R. ELPHIC, R. J. STRANGEWAY, C. A. CATTELL and R. PFAFF, 1998. FAST Observations in the Downward Auroral Current Region: Energetic Upgoing Electron Beams, Parallel Potential Drops, and Ion Heating. *Geophys. Res. Lett., 25,* 2017-2020.

CHIU, Y. T, A. L. NEWMAN and J. M. CORNWALL, 1981. On the Structures and Mapping of Auroral Electrostatic Potentials. *J. Geophys. Res., 86,* A12, 10029-10037.

CORNWALL, J. M. and Y. T. CHIU, 1982. Ion Distribution Effects of Turbulence on a Kinetic Auroral Arc Model. *J. Geophys. Res., 87,* 1517-1527.

CORONITI, F. V., 1985. Space Plasma Turbulent Dissipation: Reality or Myth?. *Space Sci. Rev., 42,* 399-410.

DELAMERE, P. A., H. C. STENBAEK-NIELSEN, D. W. SWIFT and A. OTTO, 2000. Momentum Transfer in the

Combined Release and Radiation Effects Satellite. *Physics of Plasmas, 7,* 3771-3780.

ERGUN, R. E., 1999. Magnetic-Field-Aligned Electric Fields Associated with Debye-Scale Plasma Structures. *Plasma Phys. Controlled Fusion, 41,* A61-A73.

ERGUN, R., E., C. W. CARLSON, J. P. MCFADDEN, F., S. MOZER, L. MUSCHIETTI, I. ROTH and R. J. STRANGEWAY, 1998a. Debye-Scale Plasma Structures associated with Magnetic-Field-Aligned Electric Fields. *Phys. Rev. Lett., 81,* 826-829.

ERGUN, R., E., C. W. CARLSON, J. P. MCFADDEN, F., S. MOZER, G. DELORY, W. PERIA, C. CHASTON M. TEMERIN, I. ROTH, R. MUSCHIETTI, R. J. STRANGEWAY, R. PFAFF, C. A. CATTELL, D. KLUMPAR, E. SHELLEY, W. PETERSON, E. MOEBIUS and L.KISTLER, 1998b. FAST Satellite Observations of Large Amplitude Solitary Structures. *Geophys. Res. Lett., 25,* 2041-2044.

ERGUN, R., E., C. W. CARLSON, J. P. MCFADDEN and F. S. MOZER, 2000. Parallel Electric Fields in Discrete Arcs. *Geophys. Res. Lett., 27,* 4053-4056.

ERGUN, R. E., Y. J. SU, L. ANDERSON, C. W. CARLSON, J. P. MCFADDEN, F. S. MOZER, D. L. NEWMAN, M. V. GOLDMAN and R. T. J. STRANGEWAY, 2001a. Direct Observation of Localized Parallel Electric Fields in a Space Plasma. *Phys. Rev. Lett., 87,* 045003-1–045003-4.

ERGUN, R. E., L. ANDERSON, Y.-J. SU, C. W. CARLSON, J. P. MCFADDEN, F. S. MOZER, D. L. NEWMAN, M. V. GOLDMAN and R. T. J. STRANGEWAY, 2001b. Direct Observation of Parallel Electric Fields of the Aurora, American Geophysical Union Fall Meeting 2001, abstract #SM32B-09.

ERIKSSON, A. I., A. MÄLKKI, P. O. DOVNER, R. BOSTRÖM, G. HOLMGREN and B. HOLBACK, 1997. A Statistical Survey of Auroral Solitary Waves and Weak Double Layers. 2. Measurement Accuracy and Ambient Plasma Density. *J. Geophys Res., 102,* 11385-11398.

EVANS, D. S., 1968. The Observations of a Near Monoenergetic Flux of Auroral Electrons. *J. Geophys. Res., 73,* 2315-2323.

FRIDMAN, M. and J. LEMAIRE, 1980. Relationship Between Auroral Electrons Fluxes and Field Aligned Elec-

tric Potential Difference. *J. Geophys. Res., 85,* A2, 664-670.

FÄLTHAMMAR, C.-G., 1978. Generation Mechanisms for Magnetic-Field-Aligned Electric Fields in the Magnetosphere (Invited paper GA 537 at the IAGA/IAMAP Joint Assembly, Seattle, 1977). *J. Geomag. Geoelectr. 30,* 419-434.

HAERENDEL, G., E. RIEGER, A. VALENZUELA and H. FÖPPL, 1976. First Observation of Electrostatic Acceleration of Barium Ions into the Magnetosphere, ESA Special Publ. SP-115, 203-211.

HAERENDEL, G. and R. Z. SAGDEEV, 1981, Artificial Plasma Jet in the Ionosphere. *Adv. Space Res., 1,* 29.

HAERENDEL, G., H. U. FREY, O. H. BAUER, E. RIEGER, J. CLEMMONS, M. H. BOEHM, D. D,. WALLIS and H. LÜHR, 1994. Inverted-V Events Simultaneosly Observed with the Freja Satellite and from the Ground. *Geophys. Res. Lett., 21,* 1891-1894, .

HAIRAPETIAN, G. and R. L. STENZEL, 1990. Observation of a Stationary Current-Free Double Layer in a Plasma, *Phys. Rev. Lett., 65,* 175.

HATAKEYAMA, R., Y. SUZUKI and N. SATO, 1983. Formation of Electrostatic Potential Barrier between Different Plasmas. *Physical Rev. Lett., 50,* 1203.

HESSE, M. and K. SCHINDLER, 1988. A Theoretical Foundation of General Magnetic Reconnection. *J. Geophys. Res., 93,* 5559-5567.

HESSE, M., K, SCHINDLER, J. BIRN and M. KUZNETSOVA, 1999. The Diffusion Region in Collisionless Magnetic Reconnection. *Physics of Plasmas, 6,* 1781-1793.

HULTQVIST, B., 1971. On the Production of a Magnetic-Field-Aligned Electric Field by the Interaction Between the Hot Magnetospheric Plasma and the Cold Ionosphere. *Planet. Space Sci., 19,* 749-759.

HULTQVIST, B., 2002. Downward Ion Acceleration at Auroral Latitudes: Cause of Parallel Electric Field. *Ann. Geophys., 20,* 1117-1136.

HÄUSLER, B., R. TREUMANN, O. BAUER, G. HAERENDEL, R. BUSH, C. W. CARLSON, B.

THIELE, B., M. C. KELLEY, V. S DOKUNIN and TU. YA. RUZHIN, 1986, Observations of the Artificially Injected Porcupine Xenon Beam in the Ionosphere. *J. Geophys. Res., 91,* 287.

INUTAKE, M., T. CHO, M. ICHIMURA, K. ISHII, A. ITAKURA, I. KATANUMA, Y. KIWAMOTO, Y. KUSAMA, A. MASE, S. MIYOSHI, Y. NAKASHIMA, T. SAITO, A. SAKASAI, K. SAWADA, I. WAKAIDA. N. YAMAGUCHI and K. YATSU, 1985. Thermal Barrier Formation and Plasma Confinement in the Axisymmetrized Tandem Mirror GAMMA 10. *Phys. Rev. Lett., 55,* 939.

ISHIGURO, S., K YOSHIZO and N. SATO, 1995. Potential Formation Due to Injection Along Converging Magnetic Field Lines. *Phys. Plasmas, 2,* 3271-3274.

JANHUNEN, P. and A. OLSSON, 1998. The Current-Voltage Relationship Revisited: Exact and Approximate Formulas with almost General Validity for Hot Magnetospheric Electrons for bi-Maxwellian and Kappa Distributions. *Ann. Geophys., 16,* 292-297.

KNIGHT, S., 1973. Parallel Electric Fields. *Planet Space Sci., 21,* 741-750.

LE CONTEL, O., 1999. Parallel Potential drop Associated with Unsteady Plasma Transport, AGO 1999 Fall Meeting, Abstract SM12C-04.

LE CONTEL, O., R. PELLAT R. and A. ROUX, 2000. Self-consistent Quasi-Static Parallel electric Field Associated with Substorm Growth Phase. *J. Geophys. Res. 105,* 12945-12954.

LEMAIRE, J. and M. SCHERER, 1974. Ionosphere-Plasma Sheet Field-Aligned Currents and Parallel Electric Fields. *Planet. Space. Sci., 22,* 1485-1490.

LU, G., P. H. REIFF, J. L. BURCH and J. D. WINNINGHAM, 1991. On the Auroral Current-Voltage Relationship. *J. Geophys. Res., 96,* 3523-3531.

LUNDIN, R. and I. SANDAHL, 1978. Some Characteristics of the Parallel Electric Field Acceleration of Electrons over Discrete Auroral Arcs as observed from Two Rocket Flights, SP-135, 125 136.

Lyons, L.R., D.S. Evans, and R. Lundin, 1979, An Observed Relation Between Magnetic Field Aligned Electric Fields and Downward Electron Energy Fluxes in the Vicinity of Auroral Forms. *J. Geophys. Res., 84,* 457-461.

MARKLUND, G., L. BLOMBERG, C.-G. FÄLTHAMMAR and P.-A. LINDQVIST, 1994. On Intense Diverging Electric Fields Associated with Black Aurora. *Geophys. Res. Lett., 21*, 1859-1862, 1994.

MARKLUND, G., T. KARLSSON and J. CLEMMONS, 1997. On Low-Altitude Particle Acceleration and Intense Electric Fields and Their Relationship to Black Aurora. *J. Geophys. Res., 102,* 17509 17522.

MARKLUND, G. T., N. IVCHENKO, T. KARLSSON, A. FAZAKERLEY, M. DUNLOP, P.-A. LINDQVIST, S. BUCHERT, C. OWEN, M. TAYLOR, A. VAIVALDS, P. CARTER, M. ANDRÉ, M. and A.BALOGH, 2001. Temporal Evolution of the Electric Field Accelerating Electrons Away from the Auroral Ionosphere. *Nature, 414*, 724-727.

MCILWAIN, C. E., 1960. Direct Measurement of Particles Producing Visible Aurora. *J. Geophys. Res., 65,* 2727-2747.

MENIETTI, J. D., and J. L. BURCH, A., 1981. Satellite Investigation of Energy Flux and inferred Potential Drop in Auroral Electron Energy Spectra. *Geophys. Res. Lett., 8,* 1095-1098.

MOZER, F., S. and A. HULL, 2001. Origin and Geometry of Upward Directed Parallel Electric Fields in the Auroral Acceleratrion Region. *J. Geophys. Res., 106,* 5763-5788.

MOZER, F. S. and C. A. KLETZING, 1998. Direct Observation of Large, Quasi-Static, Parallel Electric Fields in the Auroral Acceleration Region. *Geophys. Res. Lett., 25,* 1629.

MÄLKKI, A. and R. LUNDIN, 1994. Altitude Distributions of Upward Flowing Ion Beams and Solitary Waves Structure in the Viking Data. *Geophys. Res. Lett., 21,* 2243-2246.

NEWCOMB, W.A., 1958. Motion of Magnetic Lines of Force. *Ann. Phys., 3,* 347-385.

OLSSON, A. and P. JANHUNEN, 1998. Field-Aligned Conductance Values Estimated from Maxwellian and Kappa Distributions in Quiet and Disturbed Events Using Freja Electron Data. *Ann. Geophys., 16,* 298.

OLSSON, A., A.I. ERIKSSON and P. JANHUNEN, 1996. On the Current-Voltage Relationship in Auroral Breakups and Westwards-Travelling Surges. *Ann. Geophys., 14,* 1265-1273.

OLSSON, A., L. ANDERSSON, A.I. ERIKSSON, J. CLEMMONS, R. E. ERLANDSON, G. REEVES, T. HUGHES and J. S. MURPHREE, 1998. Freja Studies of the Current-Voltage Relation in Substorm Related Events. *J. Geophys. Res., 103*, 4285-4302.

PAPADOPOULOS, K., 1977. A Review of Anomalous Resistivity for the Ionosphere. *Rev. Geophys. Space Phys., 15*, 113-127.

PERRAUT, S., O. LE CONTEL, A. ROUX, R. PELLAT, A. KORTH,A., Ø. HOLTER and A. PEDERSEN, 2000. Disruption of parallel Current at Substorm Breakup. *Geophys. Res. Lett., 27,* 4041-4044.

PERSSON, H., 1963. Electric Field Along a Magnetic Line of Force in a Low-Density Plasma. *Phys. Fluids, 6,* 1756-1759.

PERSSON, H., 1966. Electric Field Parallel to the Magnetic Field in a Low Density Plasma. *Phys. Fluids, 9,* 1090-1098.

PIERRARD, V., 1996. New Model of Magnetospheric Current-Voltage Relationship. *J. Geophys. Res., 101,* 2669-2675.

PONYAVIN, D. I., M. I. PUDOVKIN and S. S. SAZHIN, 1977. Self-Consistent Field-Aligned Electric Field in the Earth's Magnetosphere. *Geomagnetism and Aeronomy, 17,* 323-325.

PRITCHETT, P. L. and F. V. CORONITI, 2002. Consequences of Current Interruption for Plasma Shett Dynamics. *J. Geophys. Res.,* in press.

RAADU, M. A., 1989. The Physics of Double Layers and Their Role in Astrophysics. *Phys. Rep., 178,* 27-97.

REIFF, P. H., H. L. COLLIN, J. D. CRAVEN, J. L. BURCH, J. D. WINNINGHAM, E. G. SHELLEY, L. A. FRANK and M. A. FRIEDMAN, 1988. Determination of Auroral Electrostatic Potentials using High and Low Altitude Particle Distributions. *J. Geophys. Res., 93,* 7441-7465.

RÖNNMARK, K., 1999. Electron Acceleration in the Auroral Current Circuit. *Geophys. Res. Lett., 26,* 983-986.

RÖNNMARK, K., 2002. The Auroral Current-Voltage Relation. Submitted to *J. Geophys. Res.*

RÖNNMARK, K. and M. HAMRIN, 2000. Auroral Acceleration by Alfvén Waves and Electrostatic Fields. *J. Geophys. Res., 105,* 25333-25344.

SAKANOI, K., H. FUKUNISHI and T. MUKAI, 1995. Relationship between Filed-Aligned Currents and Inverted-V Parallel Potential Drops Observed at Midaltitudes. *J. Geophys. Res., 100,* 19343-19360.

SATO, N., 1982. Double Layers in Laboratory Plasma, pp 116-140. *In:* Proc. Symposium on Plasma Double Layers, Roskilde 1982, Publ. by Risø National Laboratory, Roskilde.

SATO, N., Y. WATANABE, R. HATAKEYAMA and T. MIENO, 1988. Potential Formation in a High Speed Plasma Flow along Converging Magnetic Field Lines, *Phys. Rev. Lett., 61,* 1615.

SCHINDLER, K, M. HESSE and J. BIRN, 1988. General Magnetic Reconnection, Parallel Electric Fields, and Helicity. *J. Geophys. Res., 93,* 5547-5557.

SCHRIVER, D. and M. ASHOUR-ABDALLA, 1993. Self-Consistent Formation of Parallel Electric Fields in the Auroral Zone. *Geophys. Res. Lett., 20,* 475-478.

SERIZAWA, Y. and T. SATO, 1984. Generation of Large Scale Potential Difference by Currentless Plasma Jets Along the Mirror Field. *Geophys. Res. Lett., 11,* 595-598.

SINGH, N., 1993. Interaction of Field-Aligned Cold Plasma Flows with an Equatorially Trapped Hot Plasma: Electrostatic Shock Formation. *Geophys. Res. Lett.., 20,* 799.

SU, Y., R. E. ERGUN and F. BAGENAL, 2001. Io-Related Auroral Arcs: Modelling Parallel Electric Fields, American Geophysical Union 2001 Fall Meeting, abstract #P12A-0494.

SWIFT, D.W., 1992. Plasma Dynamics on Current-Carrying Magnetic Flux Tubes. *J. Geophys. Res., 97,* 2881.

TEMERIN, M. and C. W. CARLSON, 1998. Current-Voltage Relationship in Downward Auroral Current Region. *Geophys. Res. Lett., 25,* 2365-2368.

TEMERIN, M., K, CERNY, W. LOTKO and F. S. MOZER, 1982. Observations of Double Layers and Solitary Waves in Auroral Plasma. *Phys. Rev. Lett., 48,* 1175-1179.

WASHIMI, H. and I. KATANUMA, 1986. Numerical BGK-Solutions of Large Scale Electrostatic Potential in Auroral Plasmas. *Geophys. Res. Lett., 13,* 897-900.

WEIMER, D. R., D. A. GURNETT, C. K. GOERTZ, J. D. MENIETTI, J. L. BURCH and M. SUGIURA, 1987. The Current-Voltage Relationship in Auroral Current Sheets. *J. Geophys. Res., 92,* 187-194.

WHIPPLE, E.C., Jr., 1977. The Signature of Parallel Electric Fields in a Collisionless Plasma. *J. Geophys. Res., 82,* 1525-1531.

YEH, H.-C. and T.W. HILL, 1981. Mechanism of Parallel Electric Fields Inferred From Observations. *J. Geophys. Res. 86,* 6706.

---

Carl-Gunne Fälthammar

*Division of Plasma Physics, Alfvén Laboratory, Royal Institute of Technology, S-100 44 Stockholm, Sweden Email: falthammar@plasma.kth.se*