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GENERATION MECHANISMS FOR MAGNETIC--FIELD-ALIGNED ELECTRIC FIELDS IN THE MAGNETOSPHERE

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Abstract

Magnetic-field-aligned electric fields in the magnetosphere can be generated in several different ways.

Current driven wave instabilities can lead to either anomalous resistivity or electric double layers. Both can support potential drops drops of many kilovolts. In the former case this requires wave turbulence extended over large distances, because observed wave amplitudes allow only moderate field strengths. In the latter case the voltage drop is concentrated to one or more (perhaps numerous) thin regions, sometimes referred to as electrostatic shocks, each of the order of several tens of Debye lengths thick. Once established, such layers may exist with or without substantial wave turbulence. It has also been proposed that wave-particle interaction may establish a collisionless version of the thermoelectric effect. In the hot magnetospheric plasma potential drops can be created as a consequence of the magnetic mirror force. In a magnetically trapped plasma this, in principle, requires no current, although some leakage current is expected. The mirror effect has its most dramatic impact in regions of upward Birkeland currents, where it limits the current density to moderate levels unless large voltages are applied (many times the voltage-equivalent of the thermal energy of the magnetospheric plasma). The distribution of this voltage depends critically on the distribution functions of the plasma particles involved, and it may well degenerate into electric double layers.

Observational data now available indicates that more than one of the mechanisms mentioned are operative in the magnetosphere but it is not yet possible to evaluate their relative importance.

1. Introduction

Recent literature in the area of magnetospheric physics reflects a considerable interest in magnetic-field-aligned electric fields. Such electric fields can have important consequences for magnetospheric theory (Fälthammar, 1977).

The previous lack of interest in this important problem area was due to the prevalence of overidealized models of the magnetospheric plasma. In these models there was no place for mechanisms that could support magnetic-field-aligned electric fields of any significance. For this reason, early suggestions of their importance (Alfvén, 1958) went unheeded.

The reconsideration has come as a consequence of refined observations, especially of particle distribution functions, that have led numerous authors to postulate magnetic-field-aligned electric fields in explanation of their findings. It is at this time impossible to say to what extent the various postulates are correct, because direct measurements of parallel electric fields are still very scarce. However, these direct measurements (§2) although few, are exceedingly important because they 1) make it possible to say with certainty that magnetic-field-aligned electric fields do occur in the magnetosphere, and 2) give us some guidance to the magnitude and distribution of these fields.

With realistic plasma models one can identify several possible mechanisms capable of supporting significant electric field strengths along the magnetic field (Block and Fälthammar, 1976). Here we will systematically consider the existing possibilities (§3). Specific mechanisms will be discussed in the light of recent experimental evidence (§§4-7). The electric fields supported by different mechanisms will have certain distinguishing characteristics, especially in terms of strength and spatial distribution. It is concluded (§8) that probably more than one of the possible mechanisms is operative in the magnetosphere, but much more experimental evidence is required.

2. General comments and classification of mechanisms

Electric fields in the magnetosphere arise both from charge separation and from induction due to time-varying magnetic fields. In either case the integral $\int \underline{E} \cdot \underline{ds}$ between two spatially separated points generally differs from zero. If, as was previously believed, the magnetospheric plasma had a very large conductivity, its charge carriers would move to rearrange themselves so as to make each magnetic field line essentially an equipotential. This follows from the assumption of (a generalized) Ohms law, $\underline{i} = \sigma \cdot \underline{E}$ being valid, and $\sigma_{\parallel}$ (the conductivity along the magnetic field) being large. If, in any local region, $\underline{E} \cdot \underline{B}$ were non-zero, a current $\sigma_{\parallel}$ $(\underline{E} \cdot \underline{B})/B$ would flow to readjust the charge distribution and suppress $\underline{E} \cdot \underline{B}$ to (essentially) zero.

Two comments are appropriate here. First, even when the primary cause of the electric field is induction by a time-varying magnetic field, charge separation, too, is essential in determining the spatial distribution of the electric field. Even if $\partial B/\partial t$ were known exactly, this would not be enough to calculate the actual electric field in the magnetosphere. As vast numbers of charge carriers are present in the plasma, minute rearrangements are enough to thoroughly change the electric field distribution from the "pure" induction field that would apply in a vacuum. Secondly, it is interesting to note that (as emphasized by Pellinen et al., 1977) an electric induction field can only be locally extinguished by charge rearrangement. If charges are redistributed so that $E_{\parallel}$ vanishes, $E_{\perp}$ will typically be strenthened and certainly be non-vanishing.

If a finite $E_{\parallel}$ is to exist other than as a brief transient, its force on the charge carriers has to be balanced in some way. In a collision-dominated plasma, the balancing force is collisional friction due to the motion caused by the electric field.

As we will be dealing with essentially collisionless plasmas, the collisional friction is insignificant and will be disregarded. The problem of finite $E_{\parallel}$ being possible then centers around the existence of other mechanisms by which the force from the d.c. $E_{\parallel}$ on the charge carriers can be balanced. Locally this problem is exactly the same whether the electric field as a whole is inductive or potential. We therefore need not make anv further distinction between these two cases.

In a collisonless plasma there exist the followinq four possibilities of balancinq the force from the d.c. $E_{\parallel}$.

A. Forces from a.c. electric fields

In addition to the d.c. electric field, $E_{\parallel}$, there may be an a.c. electric field $\tilde{\underline{E}}$. For a steady state to exist, an average charge carrier (runaways excluded) must essentially lose as much momentum to the a.c. field as it gains from the d.c. field. This puts certain requirements on the intensity of $\tilde{\underline{E}}$, which will be discussed later.

a) It is known theoretically as well as experimentally that the force from a.c. electric fields of wave turbulence can cause substantial friction to the current-carrying electrons and establish a situation of anomalous resistivity (§4).

b) The a.c. electric force on the charged particles is likely to vary much with the particle energy and pitch angle. It has been proposed that as a consequence a collisionless kind of thermoelectric effect and a corresponding non-vanishing $E_{\parallel}$ may occur in the interface between plasmas with widely differing distribution functions (§5).

B. Forces from the d.c. magnetic field

A converging d.c. magnetic field exerts a magnetic mirror force $-\mu \cdot (\mathrm{grad}\ B)_{\parallel}$ on each charge carrier. On high latitude magnetic field lines this force is sufficient to support magnetic field aligned potential drops of many kilovolts (§6).

C. Forces from a.c. magnetic fields

Depending on the nature of the wave turbulence, it may contain mangetic a.c. fields as well. Such fields may therefore accompany anomalous resistivity and collisionless thermoelectric effect, but in the magnetosphere, their role in the force balance is negligible.

D. Inertia forces

A final possibility is that the force from the electric field is, locally, balanced only by the inertia of the charge carriers, all of which run away and carry their momentum to other parts of the current path. The relation between $E_\parallel$ and $i_\parallel$ is then not local but depends on the entire circuit. Such is the situation in the case of electric double layers (§7).

3. Observed voltages and field strengths

Even before direct measurements were available, it was clear that the magnetic-field-aligned electric fields ought to be large and/or extended enough to give voltage differences of the order of several kilovolts. Otherwise they could not play the role that they appear to play in particle acceleration. Such voltages are also enough to make $E_{\parallel}$ interesting in affecting magnetospheric plasma dynamics by partial "unfreezing" (electrical decoupling) of magnetic field lines. The recent direct observations have confirmed the expected voltages and added key information on the strength and spatial distribution of the fields.

Artificial ion-cloud experiments using shaped charges (Wescott et al., 1976, Haerendel et al., 1976) have given direct measurements of magnetic-field-aligned potential drops. In one case Haerendel et al. reported a potential drop of 7.4 kV, in good agreement with the magnitudes envisaged on other gounds. Limited spatial resolution precludes establishing the field strength in this case, and Haerendel et al. (1976) only conlude that the voltage drop occurs over 1000 km or less. This gives a lower limit of 7.4 mV/m to the field strength, but the actual field strength may well be much higher.

Direct probe measurements of d.c. electric fields at high altitude were for the first time performed by Mozer et al. (1977). These measurements revealed transverse as well as parallel electric fields of the order of hundreds of mV/m in thin regions, of the order of 3 km in transverse extent, and usually occurring in pairs. The paired regions of transverse field are expected as a consequence of magnetic-field-aligned potential drops located between them (Shawhan et al., 1977). Mozer et al.(1977) have found one clear case of very large magnetic-field-aligned electric field, hundreds of mV/m. As the large field strength implies a small vertical extent, it is consistent that such case should occur only in a small fraction of the satellite passages. The remarkably large field strength observed puts strong requirements on the responsible generation mechanisms.

4. Anomalous resistivity

Anomalous resistivity was the first mechanism to be invoked as a means to support substantial electric fields in plasmas with negligible classical resistivity. An extensive literature exists on the subject. For a recent review of the theory, with a view to space applications, see Papadopoulos (1977) and references therein.

In the present paper the emphasis will be on a physics oriented discussion of anomalous resistivity as a candidate mechanism for supporting the kind of magnetic-field-aligned electric fields now known to occur in the magnetosphere.

By definition anomalous resistivity in a strict sense implies that as a consequence of wave-particle interaction, rahter than collisional friction, there exists a local relation of the form

$$E_{\parallel} = \eta_{eff}\, i_{\parallel} \qquad (1)$$

between current density $i_{\parallel}$ and electric field $E_{\parallel}$. (The subscript " indicates that we are considering the components along the geomagnetic field.)

The wave turbulence required for this is usually assumed to be the end result of an instability driven by the current itself. However, in principle it may also be sustained by external means, such as an injected high-energy electron beam that is unstable in the local plasma environment (Papadopoulos and Coffey, 1974 a, b; Papadopoulos, 1975).

The wave turbulence will act differently on particles in different parts of velocity space. In particular, particles of sufficient initial velocity will become runaways. Those particles will become decoupled from the main population of charge carriers. The current they carry will not be determined by local conditions but depend on the whole electric circuit involved.

It is therefore interesting to note that the auroral precipitation often carries currents that are substantial fractions of the total Birkeland current. If the precipitating electrons are to be considered runaways from a region of anomalous resistivity, care must be taken in the applying the anomalous resistivity concept. The electric field - electric current relation is then not controlled by the anomalous resistivity alone. Other effects, such as magnetic-mirror or inertia forces must be considered, and the whole circuit must be taken into account.

The resistivity of a plasma, anomalous as well as classical, can be written in the form

$$\eta_{eff} = \frac{m_e}{e^2 n_e} \nu_{eff} \equiv \frac{1}{\varepsilon_o \omega_{pe}} \frac{\nu_{eff}}{\omega_{pe}} \qquad (2)$$

where ω_{pe} is the electron plasma frequency and ν_{eff} the effective collision frequency for momentum loss. In the case of anomalous resistivity ν_{eff} results from wave particle interaction. The value of ν_{eff} then depends on the actual distribution of the wave fields in $\underline{k}$ - ω - space and the distribution of charged particles in velocity space in the final turbulent state. Whereas it is straightforward to calculate onset criteria and growth rates of candidate instabilities, theoretical calculation of the nonlinear development of wave fields and particle distributions up to the final state is very difficult.

In calculating ν_{eff} it is therefore often assumed that the end result of instability growth is a turbulent state with certain simple properties. That this is not always an entirely safe method is clear from the experimentally established fact that sometimes the instability leads to double layer formation (§7) instead of anomalous resistivity.

On the other hand there is no doubt of the existence of anomalous resistivity as a phenomenon, as it has been observed experimentally in the laboratory (see e.g. Schrijver 1973 a, b and references therein). In the present discussion on the potential role of anomalous resistivity in space plasma we will largely build on results of laboratory experiments and numerical simulations rather than purely theoretical results. Values of the ratio ν_{eff}/ω_{pe} have been compiled by Schrijver (1973 b). They are reproduced in Table I.

In the present context we are especially interested in how large values of $E_\parallel$ can be achieved. If the resistivity is sustained by current-driven instability, the electron drift velocity has to have a certain minimum value. We may write the corresponding current density as

$$i_{\parallel} = 3en_e \sqrt{\frac{2kT_e}{m_e}} \qquad (3)$$

The value of β depends on the instability involved, being about unity for two-stream and Buneman instabilities, less than unity for the ion acoustic instability (typically 0.01 - 0.3). Using (1)-(3) one can now rewrite the d.c. electric field strength as

$$E_{\parallel} = \frac{kT_e}{e\lambda_D} \cdot \sqrt{2}\,\beta \cdot \frac{\nu_{eff}}{\omega_{pe}} \qquad (4)$$

Using the values of Table I we find that $E_{\parallel}$ is, at most, of the order of one per cent of the thermal voltage equivalent divided by the Debye length. Alternatively it may be written

$$E_{\parallel} = \sqrt{n_e kT_e/\varepsilon_0} \cdot \sqrt{2}\,\beta \cdot \frac{\nu_{eff}}{\omega_{pe}} \simeq 10^{-8}\beta\sqrt{n_e T_e} \qquad \text{(MKS-units)} \qquad (5)$$

The latter equation relates the achievable value of $E_{\parallel}$ to the electron-gas pressure. For example with typical plasma-sheet parameters ($n_e=10^6$ m^{-3}, $T_e=10^6$ K) we find $E_{\parallel} \simeq 10$ mV/m.

A particularly interesting question is how a d.c. electric field supported by anomalous resistivity is related to the a.c. electric field needed to support it. From consideration of the balance of momentum in the direction of the d.c. magnetic field it follows (Fälthammar, 1977; Shawhan et al., 1977) that if the d.c. electric field $E_{\parallel}$ is sustained by anomalous resistivity, then the rms value, E_{rms}, of the a.c. field has to fulfill the condition

$$E_{rms} >> E_{\parallel} \qquad (6)$$

This is essentially because the electrons gain momentum at the rate $en_eE_{\parallel}$ from the d.c. field. The momentum lost to the a.c. field depends on the actual distribution of waves and particles, but a high upper limit to its value is en_eE_{rms}.

The charge carriers' momentum component along the direction of the d.c.magnetic field can in principle also be changed by a.c.magnetic fields, $\tilde{\underline{b}}$, of turbulent waves. The instantaneous rate of momentum change for an individual particle is $e\underline{v}_{\perp} \times \underline{b}$. The vector $\underline{v}_{\perp}$ rotates at the electron gyro frequency around the total magnetic field, vector $\underline{B} = \underline{B} + \underline{b}$, which is utterly dominated by the d.c. geomagnetic field. Therefore waves of any other frequency than the electron gyro frequency have no net average effect. And even at that frequency only particles in an appropriate gyration phase lose momentum, those with opposite phase gain momentum at the same rate. The a.c. magnetic fields are therefore in practice not important in supporting an $E_\parallel$. Furthermore they would by necessity be accompanied by a.c. electric fields such that (6) would still hold.

The result (6) is quite general and applies for any anomalous resistivity whether driven by the plasma current itself or an externally imposed agent, and regardless of what instabilities are responsible for the turbulence.

For current-driven resistivity we may use the results of computer simulations to obtain a less general but more precise relation between $E_\parallel$ and E_{rms}. According to Biskamp <u>et</u> <u>al</u>. (1972) the effective collision frequency in the state of saturated turbulence satisfies the relation

$$\frac{\nu_{eff}}{\omega_{pe}} = \alpha \frac{\varepsilon_o E_{rms}^2}{2n_e kT_e} \tag{7}$$

with α = 0.2-0.3. It then follows from (1)-(3) that

$$E_{rms} = \frac{1}{\beta} \left(\frac{\omega_{pe}}{\alpha\nu_{eff}}\right)^{1/2} \cdot \quad E_\parallel \tag{8}$$

With the values of ν_{eff}/ω_{pe} given in Table I, this means that E_{rms} exceeds $E_\parallel$ by a factor of 12 to 39.

One important problem encountered in applying anomalous resistivity to space plasma is that of heat balance. Unlike the mirror effect (§6) and electric double layers (§7), the anomalous resistivity leads to local deposition of the dessipated power in the form of heat given to the local plasma (except for a certain amount that may be radiated away). The magnitude of this power per unit volume is, according to (2) and (7)

$$P = \frac{E_\parallel^2}{\eta_{eff}} = \frac{E_\parallel^2}{E_{rms}^2} \, 2\alpha^{-1} \, n_e kT_e \omega_{pe} \tag{9}$$

P can be quite large. For example, with $\beta = 1$ and the values of $E_{rms}/E_\parallel$ found above,

$$P \gtrsim \frac{n_e kT_e}{40\tau_{pe}} \tag{10}$$

where τ_{pe} is the electron plasma period.

If this power were taken up by the local plasma, it would be very rapidly heated, essentially with a time constant of only tens of electron plasma periods, or less.

Comparing with observational data we may now draw two main conclusions:

1. Extensive surveys by Hawkey (Gurnett and Frank, 1976) showed that the rms electric fields were rarely larger than 10 mV/m, although observations by Fredricks et al. (1973) show that rms fields as strong as 90 mV/m exist occasionally. In view of (6) and (7) such wave fields can support d.c. fields of the order of mV/m or less. Although unspectacular as a local phenomenon, such fields may well add up to significant potentials of several kV if extented over a few Earth radii.

2. The recent discovery by Mozer et al. (1977) of $E_{\parallel}$ with very high local field strengths - hundreds of mV/m - would require a.c. fields of several V/m if they were sustained by anomalous resistivity. Thus anomalous resistivity does not appear adequate to explain these observations but may well be operating in addition to the main mechanism (which in this case is probably double layers, §7).

5. Collisionless thermoelectric effect

The average force that a charge carrier experiences from the turbulent a.c. fields will be different for particles of different energy. In a collision-dominated plasma, where the friction force decreases rapidly with energy the result is the ordinary thermoelectric effect, which is capable of supporting a d.c. electric potential between plasmas of different temperatures, without requiring a net electric current. In the classical way we can write the magnetic-field-aligned component of the electric field

$$E_{\parallel} = - \frac{k}{n_e e} T_e^{-\gamma/2} \frac{d}{ds} (n_e T_e^{1+\gamma/2}) \tag{11}$$

where γ is the thermal diffusion coefficient which has the value 1.4 for singly charged particles in a fully ionized plasma and d/ds is the derivative along the magnetic field. The thermoelectric field vanishes only if the density n_e and temperature T_e vary in a very special way, such as to keep $n_e T_e^{1+\gamma/2}$ constant.

It has been proposed (Hultqvist 1971, 1972) that in principle the same phenomenon can occur in a collisionless plasma with energy-dependent wave-particle interaction replacing the Coulomb collisions. Of course the value of the coefficient γ would depend on how the prevailing wave particle interaction varies with energy.

To evaluate whether the thermoelectric effect plays a role in the magnetosphere will be possible only when we have much better knowledge of the height variations of the total particle distribution function (or at least of density and temperature) and, in particular, of the distribution and properties of particle scattering wave fields.

Finally we note that the arguments leading to (6) apply equally well in the case of the collisionless thermoelectric effect as it does for anomalous resistivity.

6. Magnetic-mirror effect

The magnetic mirror effect as a means to support magnetic-field-aligned electric fields in the magnetosphere was proposed by Alfvén and Fälthammar (1963).

Alfvén and Fälthammar considered the case of magnetically trapped particles. What is required in this case is a differential anisotropy between ions and electrons but no current is needed. Further theoretical studies of this case have been made by Persson (1963, 1966) and Whipple (1977). The existence of the mechanism in laboratory plasma has been established most clearly by Geller *et al.* (1974).

The potential that can be supported depends on the particle energies involved and the amount of differential anisotropy. A simple illustrative example has been treated quantitatively by Block and Fälthammar (1976) who also qualitatively discussed more realistic cases.

In the special case (delta function distributions in energy and pitch angle) treated by Alfvén and Fälthammar (1963), the electric field strength is

$$E_{\parallel} = - K \frac{dB}{ds} \qquad (12)$$

where

$$K = \frac{1}{eB} \cdot \frac{W_{e_\perp} W_{i_\parallel} - W_{i_\perp} W_{e_\parallel}}{W_{i_\parallel} + W_{e_\parallel}} \qquad (13)$$

and $W_{i_\parallel}$ ($W_{i_\perp}$), $W_{e_\parallel}$ ($W_{e_\perp}$) are the kinetic energy of ions and electrons, respectively, due to the parallel (transverse) motion. Whipple has generalized the theory to arbitrary distributions and showed that in the general case (12) holds with

$$K = \frac{1}{eB} \frac{\iint W_{e_\perp} g_e dW d\mu - \iint W_{i_\perp} g_i dW d\mu}{\iint g_e dW d\mu + \iint g_i dW d\mu} \qquad (14)$$

where

$$g = \mu^{-3/2} \left(\frac{df^+}{dW} + \frac{df_e^-}{dW} \right)_\mu (W-eV-\mu B)^{-1/2} \tag{15}$$

(in customary notation). Applying this to the magnetosphere, Whipple (1977) develops two methods for analyzing observational particle data in search of signatures of magnetic-field-aligned electric fields.

The magnetic mirror effect may be even more important in the presence of large Birkeland currents. In high-latitude flux tubes, the repulsive magnetic force on downgoing charge carriers has interesting consequences (Rassbach, 1973; Knight, 1973; Lemaire and Scherer, 1974; Lennartsson, 1976, 1977; Fälthammar, 1977).

For upward Birkeland currents the charge carriers available are upgoing ions from the ionosphere and downgoing electrons from the thin hot external plasma. Although the ions are unimpeded by the mirrors and therefore may be important (Rassbach, 1973) their capacity for carrying current is rather limited. The downgoing electrons, on the other hand suffer from magnetic mirroring, and it can be shown (Fälthammar, 1977) that for moderate electric fields this current-carrying capability can be written as a <u>conductance per unit area</u> (at ionospheric level), given by

$$\frac{di}{dV} = \frac{1}{2\pi} \varepsilon_0 \omega_{pe2} / \lambda_{D2} \tag{16}$$

where the subscript 2 refers to the external plasma.

A corresponding <u>conductivity</u> in the sense of a local relation between current density and electric field strength does not exist in this case. Typical values of this conductance for different types of source plasma are given in Table II.

We notice that the conductance is remarkably limited so that commonly occuring current densities will require voltage drops of several kV.

Unlike the total potential drop, V, the distribution of the electric fields along the magnetic flux tube is very difficult to calculate, as it depends on the distribution functions of both ions and electrons and their variations along the flux tube.

The above expression (16) and corresponding numerical values in Table II apply provided the loss of the source plasma is kept filled by continual replenishment. If not, the current will choke to still lower values.

The full current-voltage characteristic in the case of a Maxwellian source plasma has been derived by Knight (1973) and Lemaire and Scherer (1974). If we neglect the contribution from outgoing ionospheric electrons, which is cut off at a very small voltage drop, we can write the current density

$$i_{\parallel} = en_{e2}\sqrt{\frac{kT_{e2}}{2\pi m_e}}\cdot\frac{B_1}{B_2}\left[1-\left(1-\frac{B_2}{B_1}\right)\exp\left\{-\frac{eV}{kT_{e2}(B_1/B_2-1)}\right\}\right] \qquad (17)$$

the suscripts 1 and 2, referring, respectively, to the ionosperic level and the magnetosheath (Knight, 1973). A quantitative diagram of $i_{\parallel}$ versus V is given in Fig. 1.

So far we have discussed only the completely adiabatic situation and disregarded the effects of scattering. In the case discussed above, where the source plasma is continually replenished, the downgoing (although not the upgoing) plasma is isotropic and has a filled loss cone. Then mere scattering, without energy degradation, will not increase the current unless the wave distribution is such as to systematically decrease the particles' magnetic moment even in such a distribution. On the other hand, if the replenishment is incomplete so that the current is partly choked by a deficiency of charge carriers with small pitch angles, then pitch-angle scattering will alleviate the choking and tend to restore the conductance calculated above. If the scattering becomes intense enough, it may itself impede the current and establish an anomalous resistivity.

In this context it is important to notice that the mirror effect can operate even when $i_{\parallel}$ is far below the random thermal current, so that conditions may not be favourable for intense turbulence.

Although the mirror force can support large potentials along a flux tube, it can locally balance only rather moderate electric forces. As a generous upper limit to the electric field strength that it can balance locally we may take

$$E_{max} = (V + kT_{e2}/e)\,|(\text{grad } B)_{\parallel}|/B \qquad (18)$$

where V is the potential drop to the source plasma and T_{e2} is the temperature of the latter. With $(V + kT_{e2})/e$ of the order of 10 kV, it means that in the altitude range 2000 to 8000 km a high upper limit is 4 - 15 mVm^{-1}. Thus the mirror force alone cannot support the large field strength observed by Mozer et al. (1977) of parallel fields as large as hundreds of mV/m. However, it may facilitate formation of double layers or electrostatic shocks (cf. Kan, 1976; Lennartsson, 1977) and also influence the structure of such layers due to the (remote) mirroring of electrons trapped below the layer (Lennartsson, 1977).

To determine experimentally to what extent the mirror effect does play a role for maintaining parallel electric fields in the magnetosphere, comprehensive measurements of particle and wave spectra are needed together with measurements of the parallel electric field itself.

7. Electric double layers

Plasma instabilities sometimes develop into a final state that is very different from the turbulant state assumed in anomalous resistivity theory, namely into a double layer. The existence of such states has been known experimentally for a long time (Langmuir 1929). Recent experimental studies have been made by Torvén and Babič (1975, 1976) and Quon and Wong (1976). Important theoretical results have been obtained from simplified models (Langmuir, 1929; Block, 1972; Knorr and Goertz, 1974), and the BGK-solutions of the Vlasov equations (Bernstein, Green and Kruskal, 1957) provide a valuable tool for theoretical analysis of steady-state double layers. However, important problems remain unanswered, for example what the conditions are for instabilities to lead to double layer formation rather than to homogeneous turbulence.

Laboratory experiments as well as theoretical analysis are indispensable for improving the understanding of the double layer phenomenom. Numerical simulation is a valuable additional tool (Goertz and Joyce, 1975).

Thus the double layer is primarily a phenomenon that is known with certainty to exist in a laboratory plasma, and which may also exist in space plasma. Its main characteristics, as summarized in a recent review by Block (1977) are

1) The potential drop through the layer is at least equal to the thermal voltage equivalent (kT_e/e) of the coldest plasma bordering the layer.

2) The electric field is much stronger inside the double layer than outside, i.e. the positive and negative charges very nearly cancel each other.

3) Quasi-neutrality is locally violated. (Related to this fact is the thinness of the double layer - typically some tens of Debye lengths)

For space applications, it is also interesting to note that typically, but not necessarily, the mean free path is much larger than the thickness of the double layer.

Within the double layer each charge carrier is subject to a strong electric force which is, essentially, balanced only by the charge carrier's own inertia. Thus in a double layer all charge carriers "run away". This is a very important characteristic of the double layer as a means to support a voltage drop, because the power released is <u>not</u> deposited locally but can be carried away by the accelerated high-energy electrons down to low altitude where the atmosphere is an efficient energy sink. (Some dissipation may of course occur on the way down due to instability of the particle beam.) Thus the problem of energy deposition, which is serious in the case of anomalous resistivity, is essentially absent in the case of double layers.

It can be shown that the thickness L and the average electric field $\bar{E}$ of a double layer with voltage drop V can be written

$$L = \frac{1}{\gamma}\left(\frac{eV}{kT_e}\right)^{1/2}\lambda_D \qquad (19)$$

$$\bar{E} = \frac{V}{L} = \frac{\gamma e n_e}{\varepsilon_o}\left(\frac{eV}{kT_e}\right)^{1/2}\lambda_D = \gamma\left(\frac{eV}{kT_e}\right)^{1/2}\frac{kT_e}{e\lambda_D} \qquad (20)$$

The factor γ depends on the shape of the space charge distribution, which in turn may depend on the potential drop V or the current density i, as discussed further by Shawhan et al. (1977). Here we will only note that γ is typically in the range 0.01 to 0.1.

Recently several authors have discussed the possible role of double layers and related phenomena (electrostatic shocks) to the space plasma (Block, 1972, 1976; Kan, 1976; Swift, 1975; Swift et al., 1976; Kan and Akasofu, 1976; Shawhan et al., 1977), for a recent review, see Block (1977).

As shown by Shawhan et al. (1977) the model studied by Knorr and Goertz (1974) leads to such a value of γ that (20) becomes

$$\bar{E} = 3\cdot 10^{-5} n_e^{1/2} V^{1/2} \qquad \text{(MKS units)} \qquad (21)$$

while the model of Langmuir (1929) implies an average field that depends on the current density i and is given by

$$\bar{E} = 500\ i^{1/2} V^{1/4} \qquad \text{(MKS units)} \qquad (22)$$

The experiment by Quon and Wong (1976) showed a sufficiently wide and steady double layer to allow its internal electric field distribution to be resolved. The parameters were : $n_e = 10^{14}\ m^{-3}$, $T_e = 4\cdot 10^4$ K, $i = 10\ Am^{-2}$. The potential drop was 15 V and occured over a few cm (20-30 λ_D) with a maximum field strength of 500 V/m and an average value, $\bar{E}$, of about 300 V/m.

As the theoretical models are based on special simplifying assumptions, their direct application to the space plasma is questionable. Slightly safer may be to take the experimental data just quoted and scale them to space conditions using the theories only as a guide to the functional dependence on the parameters.

Table III, from Shawhan et al. (1977) shows the numerical values of $\bar{E}$ for typical space parameters. Values calculated directly from the theoretical models are higher than any fields measured to date. The ones scaled from experiment fall very well within the range of values actually measured by Mozer et al. (1977).

Furthermore, as emphasized by Block (1977) the electric field strength, of the order of 100 mV/m and density, 1-50 cm^{-3}, observed by Mozer *et al*. (1977), does mean that condition 3 above is satisfied. (As the observed spatial extent is only of the order of kilometers, div $\underline{E} \approx 0.1/10^3$, which means a net charge density $\varepsilon_0$div $\underline{E}$ that corresponds to 0.01 particles cm^{-3}, and thus a relative charge imbalance of $2 \cdot 10^{-4} - 10^{-2}$. This is a quasineutrality violation of a magnitude typical for double layers.

8. Concluding remarks

Of the mechanisms discussed, three have been demonstrated to exist in the laboratory, the remaining two are based on theoretical considerations. The characteristics of each process and the order of magnitude of field strengths that it should be able to support under space conditions have been summarized by Shawhan et al. (1977) and are given in Table IV.

Strictly speaking none of the mechanisms has been proved to operate in space. The one closest to being confirmed is the double layer. As Tabel IV shows, it is the only mechanism that can explain the strong $E_{\parallel}$ recently measured by Mozer et al. (1977). Furthermore, the derivation from quasineutrality, which occurs only in the case of this mechanism does indeed take place in the region of those strong electric fields. In addition, conditions in the regions of high-latitude Birkeland currents are such that the magnetic mirror effect and anomalous resistivity should come into play. Thus it appears likely that at least three different mechanisms contribute to supporting parallel electric fields in the high-latitude magnetospheric plasma. However, it still remains to verify this experimentally and to assess their relative importance.

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Table I

Estimates for ν_{eff}/ω_{pe} (from Schrijver, 1973b)

Author	Method	Value of ν_{eff}/ω_{pe}
Kalinin *et al*	Experiment (linear)	$1.25-2.5\cdot 10^{-2}$
Wharton *et al*	" (")	$0.83-1.25\cdot 10^{-2}$
Schrijver	" (")	$0.53\cdot 10^{-2}$
Zavioski *et al*	" (toroidal)	$0.42\cdot 10^{-2}$
Hamberger *et al*	" (")	$0.33-1.33\cdot 10^{-2}$
Biskamp	Computer simulation	$0.33-0.67\cdot 10^{-2}$

Table II

Conductance per unit area, referred to ionospheric level

Source plasma	n_{e2} 1)	T_{e2} 1)	di/dV
Plasma sheet	1 cm^{-3}	10^6K	3 $\mu A(kV)^{-1}m^{-2}$
Magnetosheath (front)	30 cm^{-3}	$2\cdot 10^6$K	60 $\mu A(kV)^{-1}m^{-2}$
Solar wind	8 cm^{-3}	$1.5\cdot 10^5$K	60 $\mu A(kV)^{-1}m^{-2}$

1) Siscoe (1973)

Table III

Estimates of parallel electric fields in double layers (from Shawhan *et al.*, 1977)

Model \ Potential drop	1 kV	10 kV
Goertz and Joyce for $n = 1\ cm^{-3}$	1 V/m	4 V/m
Goertz and Joyce for $n = 50\ cm^{-3}$	10 V/m	30 V/m
Langmuir for $i = 10^{-6} A\ m^{-2}$	3 V/m	5 V/m
Quon and Wong exp. scaled by (21) for $n_e = 1\ cm^{-3}$	0.25 V/m	0.8 V/m
Quon and Wong exp, scaled by (22) for $i = 10^{-6} A\ m^{-2}$	0.25 V/m	0.4 V/m

Table IV

Mechanisms supporting parallel electric fields
(from Shawhan et al., 1977)

Mechanism	Physical Process	Field at 1 R_E
1. Anomalous Resistivity	Electron current retarded by waves, some electrons accelerated (run-away)	< 3 mV m^{-1}
2. Thermo-Electric Effect	Potential to retard diffusion of hot electrons in presence of wave turbulence	< 3 mV m^{-1}
3. Magnetic Mirror	Hot electrons and ions mirror at different points on field line causing charge separation	< 15 mV m^{-1}
4. Double Layer	Localized charge separation maintained by $\underline{E} \cdot \underline{J}$ power input transformed into ordered linear kinetic energy	~ 1000 mV m^{-1}

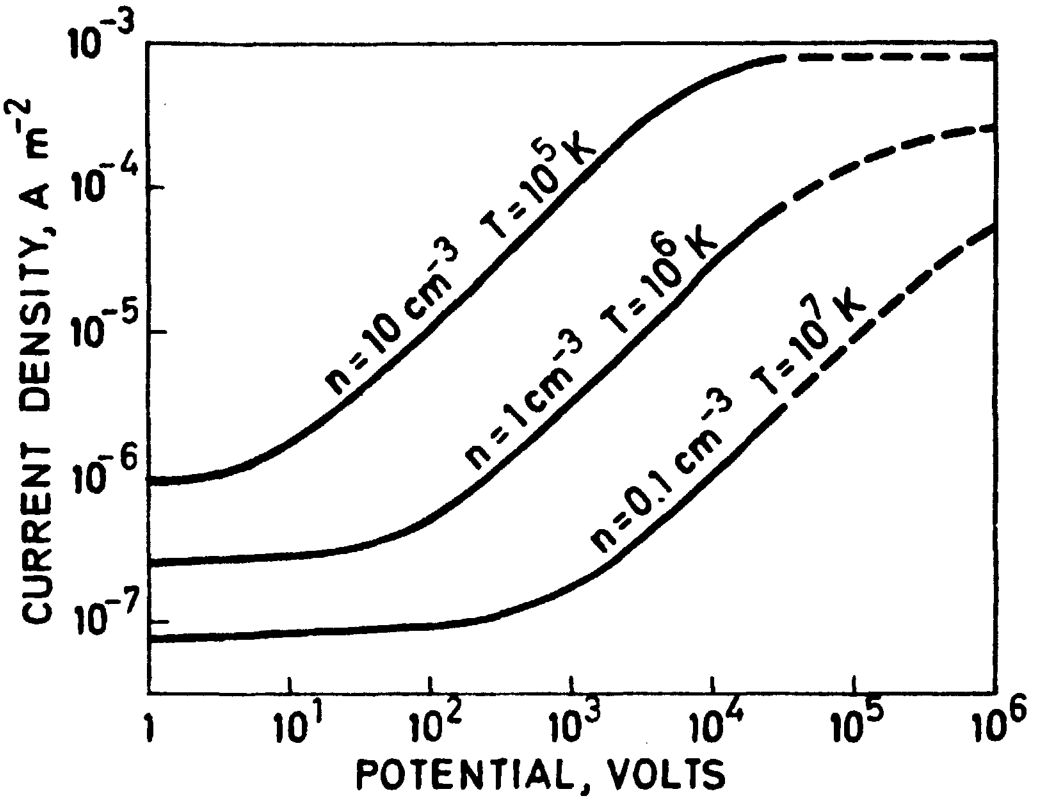

Fig. 1 Logarithmic plot of the current-voltage characteristic for three combinations of source plasma parameters typical for the plasmasheet

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GENERATION MECHANISMS FOR MAGNETIC-FIELD-ALIGNED ELECTRIC FIELDS IN THE MAGNETOSPHERE

C.-G. Fälthammar, September 1977, 28 pp, incl.ill., in English

Magnetic-field-aligned electric fields in the magnetosphere can be generated in several different ways.

Current driven wave instabilities can lead to either anomalous resistivity or electric double layers. Both can support potential drops of many kilovolts. In the former case this requires wave turbulence extended over large distances, because observed wave amplitudes allow only moderate field strengths. In the latter case the voltage drop is concentrated to one or more (perhaps numerous) thin regions, sometimes referred to as electrostatic shocks, each of the order of several tens of Debye lengths thick. Once established, such layers may exist with or without substantial wave turbulence. It has also been proposed that wave-particle interaction may establish a collisionless version of the thermoelectric effect. In the hot magnetospheric plasma potential drops can be created as a consequence of the magnetic mirror force. In a magnetically trapped plasma this, in principle, requires no current, although some leakage current is expected. The mirror effect has its most dramatic impact in regions of upward Birkeland currents, where it limits the current density to moderate levels unless large voltages are applied (many times the voltage-equivalent of the thermal energy of the magnetospheric plasma). The distribution of this voltage depends critically on the distribution functions of the plasma particles involved, and it may well degenerate into electric double layers.

Observational data now available indicates that more than one of the mechanisms mentioned are operative in the magnetosphere but it is not yet possible to evaluate their relative importance.

Key words: Anomalous resistivity, Birkeland currents, Electric double layers, Electric field, Electrostatic shock, Magnetic mirror, Parallel electric field, Space charge, Thermoelectric effect