TRITA-EPP-79-02

POTENTIAL AND INDUCTIVE ELECTRIC FIELDS
IN THE MAGNETOSPHERE DURING AURORAS

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March 1979

Submitted to Planetary and Space Science

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ABSTRACT

During quiescent auroras the large-scale electric field is essentially irrotational. The volume formed by the plasma sheet and its extension into the auroral oval is connected to an external energy source by electric currents, which enter and leave the volume at different electric potentials and which supply sufficient energy to support the auroral activity. The location of the actual acceleration of particles depends on the internal distribution of electric fields and currents. One important feature is the energization of the carriers of the cross-tail current and another is the acceleration of electrons precipitated through relatively low-altitude magnetic-field-aligned potential drops.

Substorm auroras depend on rapid and (especially initially) localized release of energy that can only be supplied by tapping stored magnetic energy. The energy is transmitted to the charged particle via electric inductive fields.

The primary electric field due to changing electric currents is redistributed in a complicated way - but never extinguished - by polarization of charges. As a consequence, any tendency of the plasma to suppress magnetic-field-aligned components of the electric fields leads to a corresponding enhancement of the transverse component.

Introduction

We can divide auroral phenomena into two main categories: quiet time auroral arcs and substorm type active auroral forms. In both cases there is considerable energy dissipation, and in both cases the energies of auroral particles have grown by at least a factor of 10 from their original values in the magnetosheath by some magnetospheric processes.

The energy of charged particles can be increased only by means of electric fields, d.c. or a.c.; this energy can be redistributed among the particles by collisions or wave particle interactions. (In the magnetosphere the former mechanism is not important.) The specific mechanisms that dominate the energization of particles may be different in different phases of auroral development. In any phase, Poynting's theorem can be used to elucidate the exchange of energy between the electromagnetic field and the kinetic energy of particles (Heikkila and Pellinen, 1977):

$$\begin{aligned} \iiint_{\tau} \underline{E} \cdot \underline{J} d\tau &= - \iiint_{\tau} \left(\frac{\underline{B}}{\mu_0} \cdot \frac{\partial \underline{B}}{\partial t} + \epsilon_0 \underline{E} \cdot \frac{\partial \underline{E}}{\partial t} \right) d\tau - \iint_{\partial \tau} \underline{E} \times \frac{\underline{B}}{\mu_0} \cdot d\underline{S} \\ &= - \iiint_{\tau} \left(\frac{\partial}{\partial t} \frac{\underline{B}^2}{2\mu_0} + \frac{\partial}{\partial t} \frac{\epsilon_0 \underline{E}^2}{2} \right) d\tau - \iint_{\partial \tau} \left(\underline{E} \times \frac{\underline{B}}{\mu_0} \right) \cdot d\underline{S} \end{aligned} \quad (1)$$

The left hand term indicates the total rate of transfer of energy given to the charged particles by the electric field. (The work done on a charged particle is $q\underline{E} \cdot \underline{v}$, and the summation $\sum q\underline{v}$ over all particles is by definition the electric current.) This energy can come from (or go to, depending on the sign) the terms on the right hand side. Those describe, respectively, the rate of change of magnetic energy, the rate of change of electric energy and the Poynting flux through the bounding surface. (The surface element vector is positive outwards.)

While it is only the electric field that can energize the charged particles, the energy density residing in the electric field is negligible compared to that in the magnetic field. For example, a magnetic field of 10 nT has an energy density of $4 \cdot 10^{-11} \text{ Jm}^{-3}$ ($=200 \text{ MeV m}^{-3}$) while an electric field of 1 mV/m has an energy density of only $4 \cdot 10^{-18} \text{ Jm}^{-3}$ ($=20 \text{ eVm}^{-3}$). Thus the electric field essentially acts as an intermediary in the transfer of energy. We should also note that the first two terms on the right hand side in (1) also include the energy residing in waves. For any wave fields, except in the ULF range, the rms amplitudes so far observed (Shawhan, 1977) or reasonably expected to exist are small enough for the contribution to the energy density to be negligible.

For the further discussion it is practical to consider separately the cases of time-independence and time-dependence in the large-scale fields corresponding respectively to quiescent and substorm auroral situations.

We will take the plasmasheet in the magnetotail as our volume τ (Fig. 1), extending dawn-to-dusk between the boundary layers, and north-to-south following magnetic field lines between and including the auroral regions in the Earth's atmosphere. We can define surfaces which limit this volume in both the sunward and the anti-sunward directions. We will discuss the first of these surfaces later. On the anti-sunward side the magnetosheath may extend hundreds of Earth radii. On the other hand the most distant parts may not couple very strongly to the auroral phenomena. At the Moon's orbit ($60 R_E$) the thickness is reduced to half and the energy density to 1/5 of what they are at $10 R_E$ (Hill, 1974). If, for convenience, we put the anti-sunward boundary of our volume at the Moon's orbit, it will include the essential parts of the magnetotail.

Quiescent auroras

In the quiet magnetosphere the large-scale magnetic fields are

essentially static and cannot be the source of auroral energy. Even the quiet-time aurora dissipates about $0.4 \cdot 10^{10} \text{ W}$ globally (Sharp and Johnson, 1968; Murphree and Anger, 1978). If this energy is to come from the magnetosheath volume defined above, it corresponds to $10^{-15} \text{ W m}^{-3}$ ($= 6 \text{ keV m}^{-3} \text{ s}^{-1}$).

The electric fields may well vary much even in the most quiet state of the magnetosphere, but their energy density is negligible anyhow, and the same is true for the wave fields.

Hence we can neglect the first two right-hand terms in (1) and have

$$\iiint \underline{E} \cdot \underline{J} \, d\tau = \iint \left(\underline{E} \times \frac{\underline{B}}{\mu_0} \right) \cdot d\underline{S} \quad (2)$$

In the term on the right-hand side (the Poynting term, which describes energy influx through the bounding surface) we must still consider wave fields as well as large-scale fields, for even though the wave fields have a negligible energy density within the volume, they could in principle transport a large flux of energy across its bounding surface. However, even if the influx were evenly distributed over a major part of the boundary it would require unreasonably large wave fields to do so. Thus, as far as the energy budget is concerned, what remains is the contribution of the macroscopic fields to the Poynting term. This term describes the energy as flowing across the boundary in the $\underline{E} \times \underline{B}$ direction. However, one must remember that Poynting's vector $\underline{E} \times \underline{B}$ itself is a mathematical abstraction, and it is only its divergence that has a physical meaning. When the large-scale electric field is curl-free, as we can assume it to be in the situation considered, we can define a potential, ϕ , such that $\underline{E} = -\text{grad } \phi$ and then rewrite the right-hand term of (2) by means of well-known vector formula $\text{curl } (\phi \underline{B}) = \phi \text{ curl } \underline{B} + (\text{grad } \phi) \times \underline{B}$, and obtain

$$\iiint \underline{E} \cdot \underline{J} \, d\tau = \oint \phi \, \underline{J} \cdot \underline{dS} \quad (3)$$

This shows that the energy supply to uphold the $\underline{E} \cdot \underline{J}$ dissipation requires that the volume considered is connected to an external source by currents that enter and leave its surface at different potentials.

We may now consider the electric currents and potentials available in the case of the magnetosphere.

From the observed structure of the magnetic field it is well established that there is a dawn-to-dusk cross-tail current of the order of 30 mA m^{-1} .

It has also been experimentally verified that there is a dawn-to-dusk cross-tail potential difference across the distant tail as manifested in lunar shadowing effects on charged-particle fluxes (Van Allen and Ness, 1969; McCoy et al., 1975). Although the strength of the field varies from ≤ 0.02 to 2 mVm^{-1} , it has an average value of the order of 0.15 mVm^{-1} corresponding to a cross-tail potential of 40 kV (the extremes correspond to ≤ 5 kV and 500 kV). This is in good agreement with the dawn-to-dusk potential fields derived from particle motion on closed field lines (DeForest and McIlwain, 1971; McIlwain, 1974) and with the direct electric field measurements on GEOS and ISEE-1 (Mozier et al., 1978; Pedersen and Grard, 1978).

The currents and potentials just mentioned (30 mA m^{-1} and 40 kV) imply that a power of 1.2 kW m^{-1} : a total of $4 \cdot 10^{11} \text{ W}$ is supplied to the magnetotail volume considered above.

As an energy supply for the quiescent aurora this is more than sufficient in magnitude.

The largest value of the average rate of input of solar wind particles to the plasma sheet that we would possibly consider is $4 \cdot 10^{27} \text{ m}^{-1}$, which

would correspond to free entry of all the particles in the solar wind intercepted by the cross-section of the magnetosphere, across which there appears the cross-tail potential difference (Heikkila, 1975). The number of particles supplied to maintain the global quiet-time auroral precipitation has been estimated by Hill (1974) to be $10^{25} - 10^{26} \text{ s}^{-1}$. (This is comparable to the number of particles which flow through the plasma mantle [Rosenbauer et al., 1975]). With $10^{25} - 10^{26}$ particles per second to share $0.4 \cdot 10^{11} \text{ W}$, an average energization of the order $0.25 - 2.5 \text{ keV}$ per particle is implied. This is likely to be divided unequally between the electrons and positive ions. As the latter are likely to be the dominating carriers of the cross-tail current, they will correspondingly receive the lion's share of the energy. However, energy may well become re-distributed from ions to electrons by secondary processes. For example, local magnetic-field-aligned electric potential drops are an important feature of the high-latitude magnetosphere (Fälthammar, 1977), and is one way in which electrons gain energy rather close to the Earth. The energy gained by the electrons is taken from the source of the electric fields, and one possible source is the kinetic energy of magnetospheric ions (which by differential drift create charge separation).

The current fed into the plasma sheet must be connected to a generator somewhere outside, i.e. a region in which $\underline{E} \cdot \underline{J} < 0$, so that the particles lose energy. Such a generator, driven by the solar wind, may be located on the sunward side of the magnetosphere; the first of the dawn-to-dusk surfaces mentioned earlier will now be defined as that surface which separates the load region with positive $\underline{E} \cdot \underline{J}$ from the dynamo region, with negative $\underline{E} \cdot \underline{J}$ (Whipple, 1978). Possible locations of the dynamo region have been discussed by Akasofu (1977) and by Heikkila (1974), but in the present context its exact location is irrelevant.

During the main growth phase of a substorm, there is a gain in stored magnetic energy within the plasma sheet (Camidge and Rostoker, 1970; Fairfield and Ness, 1970) so that $\iiint \frac{B}{\mu_0} \cdot \frac{\partial B}{\partial t} d\tau > 0$. This additional energy must also be supplied by the external generator. This means that the cross-tail current must increase during the growth phase, which will result in an inductive electric field directed from dusk-to-dawn in the equatorial plane (Murphy et al., 1975). This will tend to oppose the electrostatic field but cannot overwhelm it since an electric field supporting earthward convection still exists during the main growth phase.

Thus during quiet times, and during the main part of the growth phase of a substorm, the electric field is essentially static in nature, and we can indeed neglect time dependence. However, close to the onset time of a magnetospheric substorm this inductive field may play a significant role in the triggering mechanism, and should not be neglected (Pellinen and Heikkila, 1978b).

Substorm aurora

A magnetospheric substorm represents a rapid release of large amounts of energy, which shows up in various forms, e.g. increases in the auroral electrojets (Rostoker, 1972), enhanced auroral particle fluxes in the 1-50 keV range (Arnoldy, 1974), bursts of energetic particles (of both signs) up to at least 1 MeV (see Pellinen and Heikkila, 1978a). All these phenomena are highly localized at the time of substorm onset (Rostoker and Camidge, 1971; Untiedt et al., 1979), although with time they do grow in extent so as to eventually encompass most of the magnetosphere.

Another feature of the substorm is the deflation of the magnetotail in 10^3 to 10^4 seconds (Russell and McPherron, 1973) providing an obvious source of energy for the energization of the particles, namely the magnetic energy

represented by the first right-hand term in eq. (1).

The large-scale magnetic field changes that occur during magnetic substorms generate induced electric fields given by the Maxwell equation $\text{curl } \underline{E} = -\partial \underline{B} / \partial t$. According to Kirsch et al. (1977) rates of change of up to 2 nT per second have been observed (reporting measurements by Ness). With scale sizes up to a few Earth radii, we can conclude that the induced electric field can be quite large, up to many mVm^{-1} (Pellinen, 1978), i.e. more than a power of ten larger than the average strength of the cross-tail potential field estimated above.

Hence the magnetic field changes known to occur in substorms by necessity generate electric fields that are much larger than the preexisting static electric fields. The substorm fields may therefore be said to be essentially inductive. We will next consider the response of the plasma to these fields.

If we could entirely disregard the charged particles as contributors to the electric field, the inductive electric field, $\underline{E}_1$, could be calculated from the change in the current-density distribution $\underline{J}$. It is given by

$$\underline{E}_1 = - \frac{\partial \underline{A}}{\partial t} \quad (4)$$

using the Coulomb gauge to define a unique vector potential $\underline{A}$

$$\underline{A} = \frac{\mu_0}{4\pi} \cdot \iiint \frac{\underline{J}}{r} d\tau \quad (5)$$

(Jackson, 1975, pp. 176 and 221). Mathematically, we could have used

$\frac{1}{\mu_0} \text{curl } \underline{B}$ instead of $\underline{J}$ in (5), but in discussing physical processes involving space plasma, it is often preferable to use the electric current itself (Alfvén, 1977; Heikkilä and Pellinen, 1977).

However, as the induction field will cause differential motion of ions and electrons, there will, due to charge polarization, arise a secondary (irrotational) electric field that adds to the "pure" induction field

given by (4) and (5). As the secondary field, $\underline{E}$ due to the polarization of charges, is irrotational, it can be written as the gradient of a potential, i.e.

$$\underline{E}_p = - \text{grad } \phi \quad (6)$$

and the actual electric field, $\underline{E}$ is

$$\underline{E} = - \frac{\partial \underline{A}}{\partial t} - \text{grad } \phi \quad (7)$$

The potential ϕ and hence the actual electric field $\underline{E}$, are extremely difficult to calculate, as (1) the plasma responds on many different time scales (electron plasma period, electron gyro period, electron bounce period, the corresponding ion periods, Alfvén wave resonance times, etc., and (2) the potential ϕ depends in an exceedingly sensitive way on the actual differential displacements of positive and negative particles. In the volume considered above, a relative charge imbalance of 10^{-10} over any substantial part of the volume would be enough to generate electric fields of a strength comparable to the "pure" inductive field (4). However, regardless of the complexities involved in calculating the actual electric field we can identify a couple of important features.

1. The secondary electric field due to polarization of charges can never extinguish the induction field. We can see this by forming the line integral

around any closed contour enclosing a finite flux change

$$\oint \underline{E} \cdot d\underline{S} = \oint (\underline{E}_1 + \underline{E}_p) \cdot d\underline{S} = \oint \underline{E}_1 \cdot d\underline{S} + \oint \underline{E}_p \cdot d\underline{S} = \frac{d\Phi}{dt} + 0 \quad (8)$$

Whatever the distribution of the secondary field $\underline{E}_p$, the resultant field has to remain finite and large enough to make the line integral finite and equal to $d\Phi/dt$.

2. If the polarization of charges leads to suppression of the magnetic field-aligned electric field component $E_{||}$, the above mentioned requirement on the line integral around an arbitrary contour implies that the value of the transverse component $\underline{E}$ is enhanced instead (Heikkila and Pellinen, 1977).

The tendency toward suppression of $E_{\parallel}$ is due to the relative freedom of motion of charged particles along, as compared with transverse to, the magnetic field lines. The opposite acceleration of positive and negative particles under the influence of a transient magnetic-field-aligned component of the inductive field may explain the observations of large opposite magnetic-field-aligned flow velocities of ions and electrons in the plasmashet (Lui et al., 1978; Frank and Ackerson, 1978).

The enhancement of the transverse electric field implies a corresponding increase in $\underline{E} \times \underline{B}/B^2$ convection speeds, which will be especially large near the neutral sheet where B is small. As in some regions the transverse electric field is likely to be directed dusk to dawn, it may cause expulsion of plasma away from the Earth, perhaps in a way related to the plasma expulsion known to take place in solar flares.

3. When the net $\underline{E}_{\parallel}$ becomes small ($\underline{E}_{\parallel} = \underline{E}_{\parallel}^i + \underline{E}_{\parallel}^P \rightarrow 0$) the transverse electric field $\underline{E}_t = \underline{E}_t^i + \underline{E}_t^P$ in the ionosphere and in the magnetotail are in opposite senses, to provide a net circulation, in agreement with eq. 8 (provided that the cross-tail electrostatic field can be neglected). For example, when $d\Phi/dt < 0$ we might have a westward electric field on the night side at low altitudes (in agreement with a dawn-dusk magnetotail electric field), while at greater distances in the magnetotail along the same magnetic field lines there would be a dusk-dawn electric field. Even if an electrostatic field of external origin is added, the transverse electric field can vary in both magnitude and direction along magnetic field lines. Thus, with an induced electric field we cannot map electric fields from one region of the magnetotail to another.

Static and induced fields as agents for particle energization

As already pointed out only the electric field is able to impart energy to charged particles. As its own energy is negligible, it acts as an inter-

mediary, tapping energy either from an external source (static case) or from the magnetic field (inductive case). There are characteristic differences between the energization processes in the two cases.

As electric potential fields are conservative, the acceleration that any individual particle can experience is limited by the potential difference traversed by its orbit. (In electric fields that have a potential at each instant, but vary slowly with time, this limitation can be overcome by multi-step processes, see e.g. Falthammer [1977], but these are mainly of importance for trapped particles.) Thus an upper limit to the energy gain is of the order of 40 keV corresponding to the total potential across the magnetosphere. However, the magnetic field greatly reduces the range available to most particles, because it prohibits the particle to move across the magnetic field parallel or antiparallel to $\underline{E}$ (as would be needed for energy gain) and instead causes it to drift transverse to the electric and magnetic fields. Exceptions are (the very few) particles just at the magnetic neutral line and the particles that carry the cross-tail electric current. (The latter are mainly ions with a large dawn-to-dusk curvature drift.) But in any case the distributed character of the potential field precludes a concentrated local energization of charged particles.

Electric induction fields are in several ways more efficient for particle energization. For one thing the induction fields are larger and hence allow stronger acceleration, e.g. at the neutral line (Terasawa and Nishida, 1976, Tsurutani et al., 1976), although it has its limitations (Pellinen and Heikkila, 1978a). Another, and even more important feature of induction fields is the ability to energize charged particles locally by betatron acceleration. This, too, has its limitations. One is that the ratio of final to initial energy is given by the ratio of final to initial magnetic field strength. Hence the largest relative energy increases are again achievable

near a magnetic neutral line, where the initial field can be very small. The other limitation is due to the dependence on the particle's magnetic moment (for relativistic particles the relevant quantity is instead the flux enclosed by the gyro orbit). Only particles with a substantial magnetic moment, i.e. particles that already have a rather high energy, are efficiently energized. In particular, betatron acceleration is ineffective on "cold" plasma particles.

Near a neutral line the difficulty of energizing "cold" plasma particles can be overcome by a two-step process (Pellinen and Heikkila, 1978) where linear non-adiabatic, acceleration along the neutral line provides a sufficient momentum so that when the particle leaves the neutral line region and gets into a gyro orbit in the surrounding magnetic field, it has a sufficient magnetic moment to benefit from the betatron acceleration (Pellinen and Heikkila, 1978a; Pellinen, 1978a, b). For reasonable values of the magnetic field, charge particles accompanying a substorm may be energized to MeV energies. The dependence of the mechanism of the neutral line region also illustrates how to achieve selective acceleration, rather than an equitable distribution of available energy among the whole particle population.

Conclusions

It has been the main aim of this paper to clarify the role of static and inductive electric fields in auroral phenomena.

We have found that when the auroral oval is quiet and covered only with diffuse aurora, the energy of the aurora is supplied from an external source via electric currents that enter and leave the plasma sheet (including its extension into the auroral oval) in regions of different elec-

tric potential. An important part of the acceleration of auroral particles may still take place at localized potential drops above the auroral oval.

The active aurora, which is characterized by localized breakups, rapid expansions, large and unevenly distributed enhancements of auroral luminosity, etc., derives its energy from magnetic energy which is released in the deflation of the tail field and fed to the charged particles by the associated electric induction field.

This is necessary to explain the high rate of energy release, the uneven (initially very localized) spatial distribution of the energy release, and the selective acceleration of charged particles.

In particular, electric induction fields near a magnetic neutral line formed by the changing currents can effectively energize even zero energy particles to energies that exceed by a large factor what can be achieved by the potential difference normally available across the magnetotail.

The primary electric inductive fields can be substantially redistributed but not extinguished by polarization of charges in the plasma. The relative ease with which charged particles can move along, as compared to transverse to, the magnetic field lines may give the plasma a tendency to suppress the electric field components parallel to the magnetic field, and as a consequence enhance the transverse components. The acceleration along magnetic field lines in response to the electric inductive field may explain observed counterstreaming of ions and electrons in the tail.

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Figure 1. Poynting's theorem can be applied to the plasma sheet (shaded) as a basis for deciding whether potential or induced electric fields are important in different phases of auroral and magnetospheric activity. At the front this region should be cut off where the plasma begins to act as a generator (dotted); for convenience, the region can be terminated at the moon's orbit in the anti-solar direction.

Figure 1

TRITA-EPP-79-02

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March 1979, 18 pp. incl. ill., in English

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Key words: Aurora, Betatron acceleration, Dynamo region, Electric energy, Electric field, Electric induction, Energy density, Energy release, Energy transfer, Field-aligned acceleration, Growth phase, Magnetic energy, Magnetic neutral ine, Magnetosphere, Non-adiabatic acceleration, Parallel electric field, Particle energization, Plasma sheet, Substorm onset, Transverse electric field.