No. 66-15

AURORAL ELECTRIC FIELDS

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August 1966

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1. ELECTRIC FIELDS IN THE MAGNETOSPHERE

1.1. Introduction. A theory of the aurora must include a description of the electric fields in the magnetosphere, because such fields are important for a number of auroral phenomena. As yet, these fields have not been mapped. Information on the electric fields may be obtained from theoretical studies of the interaction of the solar wind with the magnetosphere, and processes caused by this interaction such as plasma motions within the magnetosphere. However, these difficult problems have not been solved completely. An alternative approach is to start from the other end by considering the observed auroral phenomena and finding the electric fields that would produce these phenomena. Then one has to find the process by which the fields are produced.

This paper is devoted to a discussion of the production of electric fields in the magnetosphere and some effects of these fields, viz. motion of visual and radio aurora and currents in the ionosphere. Especially, we will consider the conclusions that may be drawn about the fields from observations of these phenomena. Only static fields are considered; however, some auroral phenomena may be related to oscillating and transient fields.

1.2. Choice of frame of reference. Upon discussing electric fields in space we must remember that the field will depend on which frame of reference we use. The field $\underline{\underline{E}}'$ in a frame moving with the velocity $\underline{\underline{V}}$ relative to a frame where the field is $\underline{\underline{E}}$ is given by

$$\underline{\underline{E}}' = \underline{\underline{E}} + \underline{\underline{V}} \times \underline{\underline{B}} \qquad (1.1)$$

V is assumed to be small compared to the velocity of light. The magnetic field $\underline{\underline{B}}$ is then independent of the choice of frame of reference.

It may be suitable to use frames fixed to the earth, moving with the local neutral gas velocity, or fixed to the sun-earth line. The electric field may be quite different in these various frames.

1.3. Production of electric fields. Electric fields in the magnetosphere may be produced by several mechanisms. Different auroral theories make different assumptions as to their relative importance.

In the theories by AXFORD and HINES (1961) and DUNGEY (1961) a plasma motion within the magnetosphere driven by the solar wind induces a field. In the hydromagnetic approximation the electric field and the plasma velocity are related by the equation

$$\underline{\underline{E}} + \underline{\underline{v}} \times \underline{\underline{B}} = 0 \qquad (1.2)$$

i.e. $\underline{\underline{E}} = 0$ in a frame moving with the plasma. In this approximation, which often is used, a discussion of the plasma motion (convection) is equivalent to a discussion of the electric field distribution. Then equation 1.2 may be used to derive $\underline{\underline{E}}$ if $\underline{\underline{v}}$ is known.

However, if we want to derive theoretically the electric field distribution and the plasma motions we must use more accurate approximations. Magnetic field gradients and other effects cause the electrons and ions to move with slightly different velocities, which may bring them into different regions. Then charge separation electric fields are produced, which in turn affect the motions. FEJER (1961) and KERN (1962) have suggested that charge separation of the trapped energetic particles is the primary mechanism which produces electric fields and motions. In the auroral theory by ALFVÉN (1950) the magnetospheric electric field was supposed to be the field induced within a magnetized solar-plasma beam. KARLSON (1961) and BLOCK (1966a) have modified this theory by introducing charge separation fields. A problem, which remains to be solved, is to determine to which extent the separating charges are discharged and the plasma motions braked by currents flowing to the ionosphere.

Electric fields are also induced in the ionosphere by the winds blowing there, and polarization fields are produced when electric currents in the ionosphere flow through regions of varying conductivity. In the theories by COLE (1960) and SWIFT (1963) the ionospheric winds have been assumed to produce the auroral electric fields, but the winds are probably too weak to be of major importance (BOSTRÖM, 1964).

As seen from the sun, electric fields are also induced by the rotation of the ionosphere. It has been suggested by FEJER (1963) and TAYLOR and HONES (1965) that the magnetospheric convection (or electric field) is primarily established by the earth's rotation, but modified by the solar wind-magnetosphere interaction.

<u>1.4. Electric fields along the magnetic field lines.</u> Depending on the properties of the plasma in the outer magnetosphere, various mechanisms may produce electric fields, $\mathbf{E}_{\parallel}$, along the magnetic field lines. ALFVÉN and FÄLTHAMMAR (1963) have introduced the terms "low-density plasma" and "medium-density plasma" to distinguish between plasmas where the mean free path of the electrons is longer than the characteristic length of the region considered or shorter than this (but still longer than their gyroradius).

1. ALFVÉN and FÄLTHAMMAR (1963) have suggested that the magnetospheric plasma is of "low density". Then a considerable electric field must exist along the field lines in this "ion-exosphere" to preserve the electrical neutrality, if the pitch-angle distributions of electrons and ions are different (PERSSON, 1963). BLOCK (1966b) has recently applied this theory to auroral problems.

2. Currents must flow along the field lines to drive the auroral electrojets (see section 5). If the plasma is of "medium density" the ohmic resistance will produce an electric

field. It is difficult to estimate this field, since the geometry of the current system is unknown.

3. SWIFT (1965) has suggested that the currents along the field lines may generate ion acoustic waves by a two-stream instability. Such waves may give a high effective resistivity and a high voltage drop along the field lines. The resistivity proposed by Swift is a factor 5×10^3 higher than the ohmic resistivity of a highly ionized medium-density plasma at 1500°K.

In any case the total voltage drop along the field lines cannot be larger than about 10 kv, otherwise the precipitating particles would have too high energy.

<u>1.5. Coupling of electric fields between the outer magnetosphere and the ionospheric E and F layers</u>. We should expect that any large-scale fields transverse to the magnetic field, which are produced in one region, will be mapped onto other regions by conduction along the magnetic field lines. Since a finite voltage drop does exist along the field lines, this is not necessarily true for small-scale fields. In the ionosphere the transverse field is about 10 to 100 mv/m. If the voltage drop is different along different magnetic field lines, but less than 10 kv, fields of a scale < 10 kv $(100 \text{ mv/m})^{-1} = 100$ km at E layer heights are not necessarily images of the magnetospheric fields. On a large scale, however, the distribution of electric fields in the E layer and in the equatorial plane of the magnetosphere must be related.

2. MOTION OF AURORAL PRIMARY PARTICLES AND VISUAL AURORA

<u>2.1. The source of the visual aurora and its motion</u>. The light emission from ordinary polar auroras is produced by precipitating electrons which excite the atmospheric constituents. The lifetime of the excited states is generally very short. However, it is about 0.75 sec for the important green oxygen line (5577 Å). Since the neutral gas velocity is at most

about 100 m/sec, the light is emitted within about 100 meters from magnetic field lines along which electrons precipitate.

Thus the location and motion of the visual aurora is related to the position and motion of the source of the primary electrons. The source may be visualized as a group of primary particles in the outer magnetosphere drifting in the electric and magnetic fields, as will be described below. However, it must be noticed that motions also may be produced by "switching" on and off various stationary sources. Some very rapid motions ($>$ 10 km/sec) are probably related to some kind of wave motion.

<u>2.2. Motion of auroral primary electrons.</u> The auroral primary particles have a mean free path much larger than the linear scale of the magnetosphere, but a small radius of gyration. We may use the guiding center approximation to study their motion. If the aurora occurs on closed dipole-like field lines, the guiding center has a rapid bounce motion along the field lines between the mirror points (if it does not precipitate) and a slow drift transverse to the magnetic field. The latter has two components, one due to the electric field and one due to the gradients of the magnetic field.

To find the time it takes for a particle to drift from one field line to another, the velocities are projected along the field lines onto the ionospheric E layer and integrated over one bounce period. The projected drift velocity $\underline{\underline{U}}_E$ produced by $\underline{\underline{E}}$ is independent of where along the field line the particle is (if curl $\underline{\underline{E}}_{\parallel} = 0$). It is given by

$$\underline{\underline{U}}_E = \underline{\underline{E}}_i \times \underline{\underline{B}}_i / B_i^2 \qquad (2.1)$$

where $\underline{\underline{E}}_i$ and $\underline{\underline{B}}_i$ are the fields at E layer heights. The ∇B drift in a dipole field has been studied by HAMLIN et al. (1961). For particles which reach the E layer of the auroral zone

$$U_B(\text{m/sec}) = 0.03\ W(\text{ev}) \qquad (2.2)$$

directed eastward for electrons and westward for protons. W is the total kinetic energy of the particle.

If the source is a blob of enhanced particle density, the ∇B drift will separate the electrons and ions. A charge separation field is produced which will push the blob in the direction of decreasing magnetic field. The general magnetospheric electric field can bring the blob into a stronger magnetic field to the point where the charge separation field cancels the general field at the blob. To some extent the space charges may be neutralized by particles from the ionosphere. An upper limit of this neutralizing effect may be obtained by assuming a perfect coupling to the ionosphere, but taking into account the finite transverse conductivity in the ionosphere (KERN, 1964). The motion of blobs is evidently dependent on the unknown coupling to the ionosphere. However, we are not going to deduce the motion, but deduce the electric field from the observed motion. Then we obtain the field at the source region, which may differ from the general magnetospheric field.

2.3. Conclusions about the electric fields. The ∇B drift given by equation 2.2 is not negligible. If we know that the aurora occurs on closed field lines and if the energy W of the primary particles is known, we may compute $\underline{\underline{U}}_B$. Since the observed velocity $\underline{\underline{U}}_o = \underline{\underline{U}}_E + \underline{\underline{U}}_B$, we may then deduce the electric field from $\underline{\underline{U}}_o$ using equation 2.1. An estimate of the energy of the electrons which produce the visible aurora may be obtained by studying the luminosity profile (BELON et al., 1966). Most of the luminosity is produced by electrons with $W < 10$ kev, i.e. $U_B < 300$ m/sec.

The primary particles will in general have an energy distribution and according to equation 2.2 various ∇B drifts. The observations that auroral forms never overtake each other and that all parts of rays (which are produced by particles of various energies) move at the same velocity (COLE, 1963) suggest that the ∇B drift is not important. This may be the case if the primary particles come directly from the neutral sheet in the tail of the magnetosphere or if the particles are energized by electric fields along the magnetic field lines.

Auroral forms are generally seen to move westward before midnight and eastward after midnight on the equatorward side of the auroral belt. The velocities are of the order of 1 km/sec, while the velocities in the north-south direction are an order of magnitude smaller (COLE, 1963). An eastward drift velocity of 1 km/sec corresponds to a southward field of about 50 mv/m at E layer heights measured in a frame of reference fixed to the earth. Before midnight the field should be in the opposite direction.

However, it has been pointed out by AKASOFU (1965) that the motions in the evening and morning are different in many ways. The westward motions in the evening are characterized as propagation of deformations along the auroral forms, while in the morning patches drift as a whole eastward. Akasofu suggests that only the latter motions are related to the electric fields.

3. EFFECTS OF IONOSPHERIC ELECTRIC FIELDS

3.1. Electric currents. Since the conductivity along the magnetic field lines is much higher than transverse to these, we may in general neglect voltage drops along the field lines in the E and F layers. The coupling between various levels above 100 km is almost perfect for fields of a scale larger than a few kilometers (REID, 1965). Thus $\underline{\underline{E}}_\perp$ is independent of height, and if the neutral gas velocity $\underline{\underline{v}}_n$ is also independent of height or small, we have the following expression for the height integrated current density $\underline{\underline{I}}_\perp$ in terms of the height integrated conductivities Σ

$$\underline{\underline{I}}_\perp = \Sigma_P(\underline{\underline{E}}_\perp + \underline{\underline{v}}_n \times \underline{\underline{B}}) + \Sigma_H \underline{\underline{B}} \times (\underline{\underline{E}}_\perp + \underline{\underline{v}}_n \times \underline{\underline{B}})/B \qquad (3.1)$$

For a night-time ionosphere the Pedersen conductivity $\Sigma_P^N \approx 1$ mho and the Hall conductivity $\Sigma_H^N \approx 0.5$ mho and for an auroral excited region (maximum electron density 10^6 cm^{-3}) $\Sigma_P^A \approx 30$ mho and $\Sigma_H^A \approx 50$ mho (MAEDA and MATSUMOTO, 1962; KIM and KIM, 1963; BOSTRÖM, 1964). Previously it has often been assumed that $\Sigma_P << \Sigma_H$ which does not seem to be correct.

3.2. Motion of irregularities. The auroral ionization irregularities are generally field aligned. It has been shown (CLEMMOW et al., 1955; KATO, 1965) that such irregularities will propagate with the velocity

$$\underline{\underline{V}} = \underline{\underline{v}}_n + (1 + \nu_e \; \nu_i / \omega_e \; \omega_i)^{-1} \; (\underline{\underline{E}} + \underline{\underline{v}}_n \times \underline{\underline{B}}) \times \underline{\underline{B}}/B^2 \qquad (3.2)$$

This expression is strictly valid only if the collision and gyro frequencies, ν and ω, do not vary with the height. However, above 100 km $\underline{\underline{V}}$ is very close to $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$, and there the formula may be used for extended irregularities. In this expression the electric field at the irregularity should be used. In general this is different from the external field due to polarization effects; it may be determined by applying the condition div $\underline{\underline{I}}_{\perp} = 0$. Then we neglect currents parallel to $\underline{\underline{B}}$ above the F layer. This may be correct for small scale irregularities and in any case it will give an upper limit for the polarization effects.

Expressions for the internal field in a slab irregularity (a model of a homogeneous auroral arc) have been discussed by BOSTRÖM (1964). Using the conductivities given above and assuming the external field E^N to be parallel to the irregularity we find that a polarization field $E^A \approx 2\; E^N$ is produced transverse to the irregularity. The transverse motion of the irregularity will not be affected by this field, neither will it be affected by motions of the neutral gas if the irregularity is located above a height of 100 km.

The corresponding expressions for a cylindrical irregularity have been given by HAERENDEL et al. (1966). For the conductivities given above we find that the internal field $E^A \approx 0.03\; E^N$. $\underline{\underline{E}}^A$ is inclined at an angle of 60° relative to $\underline{\underline{E}}^N$ in the direction of $\underline{\underline{E}}^N \times \underline{\underline{B}}$. Such a strong irregularity, with a finite extension in all directions transverse to $\underline{\underline{B}}$, moves with a speed much less than E^N/B. If $\underline{\underline{v}}_n \neq 0$, this will give a contribution to the velocity of the irregularity, which is almost equal to $\underline{\underline{v}}_n$.

Since the internal field is homogeneous in these two cases, the irregularities may move without changing their shape.

In the absence of any source of auroral ionization the irregularities will decay due to dissociative recombination. In the E layer the recombination coefficient is about 3×10^{-7} cm^3 sec^{-1}. An irregularity of initial density 10^6 el/cm^3 is reduced by a factor 2 in a time of about 3 sec. However, the density is more than twice the density of the undisturbed ionosphere for about 1000 sec, if the latter density is assumed to be 2×10^3 el/cm^3.

4. MOTION OF AURORAL IONIZATION

4.1. Introduction. The precipitating electrons that produce visual aurora will also produce regions of enhanced ionization, "radio aurora". Although the visual and radio auroras are produced at the same place, their motion may be different. The life time of the ionization is considerable, thus its motion is not only due to motions of the source, but also to the effect of electric fields in the ionosphere.

4.2. Correlation with visual aurora. If the ionization source (which coincides with the visual aurora) does not move with the same velocity as ionization irregularities, the regions of enhanced ionization may separate from regions of visual aurora. If we consider only strong irregularities the separation will not be great, since they decay in a few seconds and the observed velocities are of the order of 1 km/sec. For weak irregularities a considerable separation may occur, and such irregularities may remain for a considerable time after a visual aurora has disappeared.

If the following conditions are fulfilled the source and the irregularity will move synchronously with the velocity $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$, and no separation occurs. (1) $\underline{\underline{E}}_{\parallel} = 0$ or curl $\underline{\underline{E}}_{\parallel} = 0$, i.e. good coupling of the electric fields between the ionosphere and magnetosphere. (2) The ∇B drift is negligible. (3) The height of the irregularity > 100 km (otherwise it moves with a speed $< E/B$ and E is reduced). (4) v_n must be small.

If the irregularity is an auroral arc (thickness $\approx$ 10 km, length $\gtrsim$ 1000 km), i.e. a slab irregularity, it is only velocities transverse to the arc which can produce a separation. No velocities in this direction occur if (1) the arc is aligned in the direction of the ∇B drift (in general the east-west direction on the earth), if such drifts are important, (2) $\underline{\underline{E}}_\perp$ is perpendicular to the arc, and (3) v_n is small or the arc is located at a height $\gg$ 100 km. If condition (2) is not fulfilled, but the arc is above a height of 100 km, the visual aurora and the region of enhanced ionization will have the same velocity transverse to the arc. We must expect a good coupling to the source region, since the field along the arc extends over distances of the order of 1000 km. In general we should expect a good correlation between visual auroral arcs and regions of enhanced ionization.

<u>4.3. Conclusions about the electric fields</u>. The radio auroras are observed to move with about the same speeds and in the same directions as visual auroras (COLE, 1963). If the conditions discussed in section 4.2 are fulfilled, the motions should be interpreted as $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$ drift velocities. The general conclusions about the electric fields should be the same as in section 2.3. The field computed from the motion of radio aurora is the field within ionospheric irregularities, which is different from the external field but may be related to this, cf. section 3.2.

If the coupling between the ionosphere and magnetosphere is not perfect, small scale irregularities may be expected to move with a velocity different from that of the visual aurora. Due to observational difficulties (absorption and aspect sensitivity of radio observations) it has not been possible to show whether this is the case. Experiments where the motion of artificially injected ion clouds (which are visible) are observed (HAERENDEL et al., 1966) may be used to study the coupling. If such experiments are carried out in or above a region where visual auroral irregularities occur, and the velocities of the ion cloud and the aurora are compared, it may be possible to draw some conclusions about the coupling between the ionosphere and magnetosphere.

5. IONOSPHERIC CURRENTS

5.1. The DS current system. The ionospheric currents, which produce local magnetic disturbances in the auroral zone, must be driven by electric fields. Since the conductivity in the ionosphere is fairly well known, the electric field may be computed if the current density is known.

The magnetic disturbances are usually represented by an equivalent current system, the DS system, which is assumed to flow horizontally in an ionospheric shell. The real current system must include currents along the magnetic field lines, because the currents are driven by a "dynamo" in the outer magnetosphere. Thus, the DS system is not the true current system. It cannot be used directly for a derivation of the electric fields, although this has been done sometimes, for example by TAYLOR and HONES (1965). The present author does not agree with Taylor and Hones when they call their field "a carefully derived representation of the electric field".

The motions of the visual aurora generally proceeds in a direction opposite to that of the DS currents. If the motions are interpreted as $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$ drift velocities this implies that the DS currents flow in the direction of the Hall currents. Either the Hall conductivity dominates over the Pedersen conductivity, or the Pedersen currents do not produce any magnetic disturbances observable on the ground. Since all recent estimates of the height integrated Hall and Pedersen conductivities show that they are of the same order of magnitude, we would prefer the latter explanation, although many theorists have used the former.

A model of the auroral current system which has the required properties is shown in Figure 1 a. A radial electric field is produced in the equatorial plane by an azimuthal plasma motion. The field is transferred to the auroral ionosphere, where it is directed equatorward and drives a westward

Hall current (the electrojet). The Pedersen current and the current along the field lines form a current system that will produce a westward magnetic disturbance within the current system but no disturbance on the ground. The current transverse to the magnetic field in the outer magnetosphere brakes the motion, i.e. the dynamo is loaded. The $\underline{\underline{i}} \times \underline{\underline{B}}$ force is balanced by the inertia force $nm(\underline{\underline{v}} \cdot \nabla)\underline{\underline{v}}$.

The main effect of the currents along the field lines is to turn the magnetic field vector without changing its magnitude. To detect these currents it is necessary to perform directional magnetic field measurements from satellites. Recently ZMUDA et al. (1966) have found local disturbances at a height of about 1000 km over the auroral zone which may be related to the currents discussed here.

According to some observations the magnetic disturbances are proportional to the maximum electron density in the auroral sporadic E layers (NAGATA, 1963). This indicates that variations in the magnetic disturbance are produced mainly by varying amount of precipitation, which produce variations in the conductivity, while the electric field is approximately constant.

5.2. The auroral electrojets. The most intense part of the DS current system, the auroral electrojets, is probably confined to regions of enhanced ionization such as auroral arcs. It has been shown in a number of investigations that the magnetic disturbance vector often is perpendicular to auroral arcs. There are often several parallel arcs present. The current that must flow along each arc to produce a moderate disturbance is of the order of 3×10^4 amp. Assuming that the ionospheric currents in the model of Figure 1 a are confined to a 10 km thick arc and using the conductivities given in section 3.2., we find that an equatorward electric field of about 60 mv/m must exist in the ionosphere to drive the westward electrojet. This model requires a good coupling between the ionosphere and the magnetosphere.

However, there exist also other possibilities to drive the electrojets. We may apply a westward field to the auroral zone from outside (i.e. an azimuthal field in the equatorial plane) as in Figure 1 b. This tends to drive a westward Pedersen current and a northward Hall current. The latter is prevented from flowing since the conductivity outside the auroral region is much smaller. A secondary southward directed polarization electric field is produced as described in section 3.2.. The total field is directed so that the total current flows westward. If the secondary field is confined to such narrow features as auroral arcs, it is possible that it is not transferred to the outer magnetosphere.

These and other models of the auroral current systems have been discussed by BOSTRÖM (1964, 1966).

6. CONCLUDING REMARKS

Obviously many problems remain to be solved before it is possible to make a detailed derivation of the electric fields from auroral observations.

The motion of visual and radio auroras are probably primarily $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$ drifts of the source region and the auroral ionization. However, for the visual auroras, ∇B drifts may also be important, and some kinds of motions are probably produced by other mechanisms. The auroral ionization may be affected by motions of the neutral gas, and below a height of 100 km the velocity of irregularities is less than $\underline{\underline{E}} \times \underline{\underline{B}}/B^2$.

The ionospheric currents cannot be used for a detailed derivation of the electric field, since we do not know the real current systems. Only order of magnitude estimates can be made.

We must also notice that the field derived from auroral observations may be characteristic only for regions affected by the auroral particles. An unsolved problem of major importance for the dynamics of the aurora and the interpretation of the observations is to determine the coupling between the outer magnetosphere and the auroral ionosphere.

However, it is encouraging to find that the order of magnitude estimates of the electric field derived from different kinds of observations agree. They also agree with the order of magnitude of the magnetospheric field deduced theoretically by BLOCK (1966a) and the ionospheric field used by MEGILL and CARLETON (1964) to explain the excitation in high red arcs.

The order of magnitude of the auroral electric field is 50 mv/m in the E layer or a few millivolts per meter in the outer magnetosphere measured in a frame of reference fixed to the earth.

We expect that experiments, where the electric fields in space are measured directly or where ion clouds are injected, will contribute much to our understanding of the phenomena discussed in this paper.

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FIGURE CAPTION

Fig. 1. Two different auroral current systems which produce similar magnetic disturbances, DS, on the ground.

a. Only the Hall current contributes to DS.

b. Both the Hall and Pedersen currents contribute to DS.

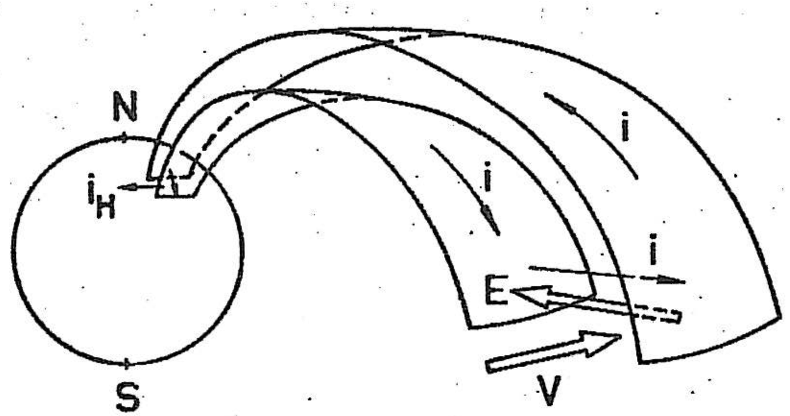

Fig. 1a

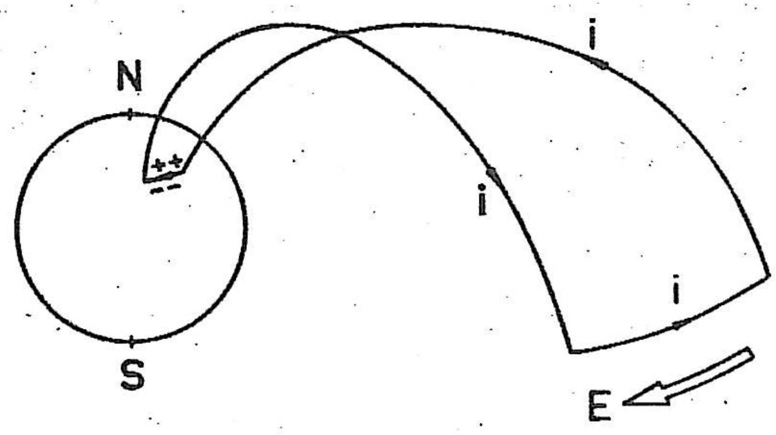

Fig.1b

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Rolf Boström (August 1966) 18 p. incl. illus.

Presented at the Advanced Study Institute "Aurora and Airglow", Keele, England, 1966.
(Rept. 66-15)

Abstract. Various mechanisms for the production of electric fields in the magnetosphere and ionosphere are reviewed. The motion of visual and radio aurora and the currents in the ionosphere are related to these fields. The possibilities to deduce the fields from auroral observations are discussed. The importance of the coupling between the ionosphere and outer magnetosphere is stressed.

Index information.

Key Words: AURORAL ELECTRIC FIELD
IONOSPHERIC ELECTRIC FIELD
MAGNETOSPHERIC ELECTRIC FIELD

Electric field derived from motions of visual and radio aurora and ionospheric currents.