PAPER 34

THE PRESENT STATE OF THE ELECTRIC FIELD THEORY OF MAGNETIC STORMS AND AURORAE

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ABSTRACT

The main features of the electric field theory are outlined. The theory should be considered as a first approximation. The validity of the approximations and assumptions introduced is discussed.

Some model experiments on the theory are described. It is impossible to construct an entirely true model of nature in the laboratory. The similarities and differences between nature and model are discussed.

The mechanism of the model seems to be described very well by the theory. Some experimental results, which because of the complicated phenomena cannot be predicted by the theory, are compared with observations in nature. As far as we can see at present, the agreement between nature and model is astonishingly good.

1. INTRODUCTION

During the last few years the electric field theory of aurorae and magnetic storms has made some progress, both theoretically and experimentally by model experiments performed at this institute. In this paper I will briefly present the results of this work and discuss it in some detail, and also point out some problems, still doubtful or unsolved.

Aurorae and magnetic storms must be consequences of the electromagnetic state in space around the earth. If, therefore, we assume some special electromagnetic state as a probable cause of the phenomena, and then work out the consequences of this electromagnetic state, we may judge about the correctness of our assumption.

2. THEORY

The electric field theory is based on the assumption, that an electric field exists in the surroundings of the earth. How this field is produced is immaterial, but it may be an effect of a cosmical wind in interplanetary space, e.g. a beam from the sun. The normal direction of the field should be from the evening side towards the morning side of the earth in order to agree with the diurnal variation of aurorae and magnetic disturbances during a storm.

Starting from this basic assumption the main problem is to calculate what happens to charged particles acted on by this electric field in the presence also of the geomagnetic field. It is certainly impossible to do this exactly, and, therefore, it is necessary to simplify the problem by physically sound approximations. At the present state of our knowledge about electrical discharges in magnetic fields it is very difficult to judge the soundness of the approximations made in the theory. The following approximations and assumptions are made:

1. The electric field is as a first approximation taken to be homogeneous and perpendicular to the magnetic dipole axis of the earth. This means that all space charges are neglected.

2. The geomagnetic field is approximated by a dipole field.

3. An interplanetary magnetic field exists ($\approx 10^{-5}$ gauss), and it is homogeneous and parallel to the geomagnetic dipole axis. (This is only essential for the theory of the initial phase.)

Having made these approximations it is possible to calculate the electronic and ionic drift orbits in the magnetic equatorial plane. These orbits are seen in Fig. 1. The earth's centre is at the origin of the co-ordinate system. The real particle orbits are trochoids along the drift orbits. At the great circle, indicated in the figure, ($R \approx 30$ earth radii) the interplanetary and geomagnetic fields are approximately equal. Because of the gradient of the magnetic field in this region the particles from the sun are retarded, and the inertial forces deflect them in such a way that they produce an eastward ring-current, which causes the increase of the geomagnetic field at lower latitudes, observed during the initial phase of a storm. Nearer the earth the inhomogeneity of the magnetic field gives a drift motion of the electrons around the earth, producing a westward current responsible for the general decrease of the geomagnetic field during the main phase of a storm. There will also be a forbidden space (mean radius about 7 earth radii), which neither the electrons nor the ions can enter. All this is described in more detail by Alfvén [1, 2].

So far the calculations of the orbits in the equatorial plane are quite rigorous, provided the density of the beam is infinitely low, so that all space charges can be neglected. However, this is by no means the case, and therefore we must in some way account for the effects of the space charges, and also for the motion of the particles above and below the

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equatorial plane. The following assumptions are supposed to account for this.

4. Particles not moving entirely in the equatorial plane are oscillating through this plane along the magnetic-field lines from north to south and back again, at the same time as they drift perpendicular to the field in orbits similar to those calculated for particles in the equatorial plane. These orbits are, therefore, of fundamental importance and may be considered as a framework for the motion of all particles.

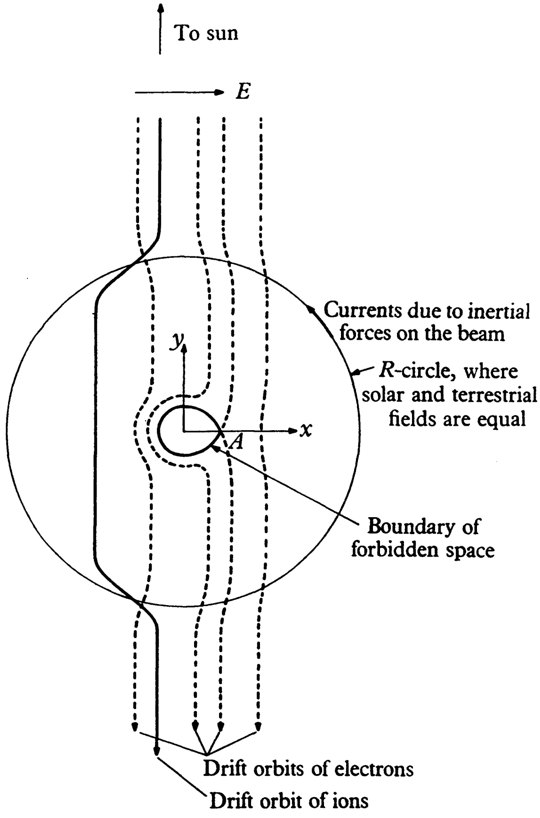

Fig. 1. Currents and particle orbits in the geomagnetic equatorial plane with an electric field perpendicular to the geomagnetic dipole axis.

5. Space charges will certainly be produced, but they will discharge along the magnetic-field lines towards the ionosphere. It is assumed, that the space charges will never be so large, that the motion shown in Fig. 1 is fundamentally changed.

Most space charges are produced at the boundary of the forbidden space and at the *R*-circle, where the interplanetary and geomagnetic fields are approximately equal (see Fig. 1). These space charges will discharge towards the auroral zones, so that the main auroral zones form the projection of the boundary of the forbidden space along the magnetic-field lines upon the earth's surface, and the inner auroral zones are the projections of the R-circle.

It is difficult to judge about the validity of the assumptions of the theory. Certainly there are sufficiently many charged particles to form considerable space charges, if sufficient charge separation occurs somewhere. This would make approximation 1 entirely invalid. Mathematically, it can be expressed as

$$e.n \gg \operatorname{div} \epsilon_0 \boldsymbol{E}; \tag{1}$$

n = number density of charged particles,

e = electronic charge,

ϵ_0 = dielectric constant of vacuum,

$\boldsymbol{E}$ = electric field.

Eq. (1) is always fulfilled in cosmical physics. But we do not know anything about to what extent charges will be separated. If assumption 5 is correct, charge separation is largely compensated by the currents along the field lines.

Another phenomenon, which is likewise not at all understood at present, are the instabilities of a plasma in a magnetic field. It is well known from investigations by Åström [3]; Massey and collaborators [4] and Webster [5], that a plasma is unstable in a magnetic field, so that a bunching of the particles takes place, and this makes it easier for the charged particles to diffuse perpendicular to the magnetic-field lines.

In particular the experiments by Webster are interesting. He produced an electron beam, shaped like a hollow cylinder. Parallel to the axis of the cylinder he applied a magnetic field. The electrons moved along the field lines. Plate I (*a*) shows the beam near the cathode and Plate I (*b*) far from the cathode. It is seen that the beam is broken up very strongly.

Recently Bostick [6] has investigated the properties of such plasma bunches, called plasmoids. We do not know whether they will affect the properties of the auroral discharge as outlined in the electric field theory.

Thus, it may be fair to say, that at the present state of our knowledge it is in principle impossible to treat the problem by ordinary theoretical methods. The best we can do is to account for the phenomena, which we believe to be most important, and to check the results by comparison with the observational results in nature, and as far as possible, by model experiments in the laboratory.

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3. MODEL EXPERIMENTS

The theory has been simulated by model experiments in the laboratory by Malmfors [7] and by Block [8].

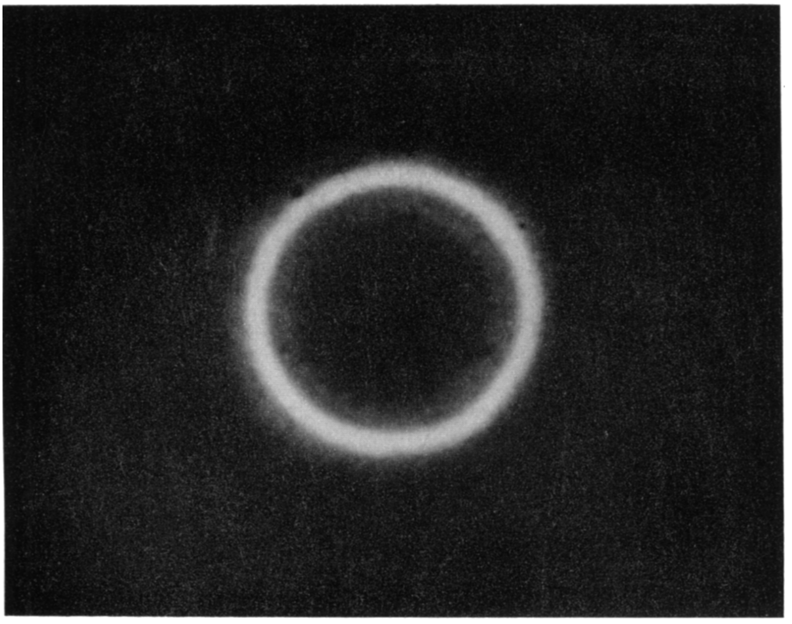
In a vacuum chamber an electric field is applied between two condenser plates. In this electric field a terrella is placed. The terrella is magnetized by a coil inside it, with the magnetic dipole axis usually perpendicular to the electric field. By some ionizing device a gaseous discharge is started around the terrella. The discharge may be self-sustained (glow discharge, Plate II (*a*)) or non-self-sustained (dark discharge, Plate II (*b*)) where the ionizing agent must be in continuous operation. The surface of the terrella is covered by fluorescent material, so that one can see where the particles impinge.

There is no doubt, that the general character of the model discharge is in agreement with the theory. Luminous eccentric ring-shaped auroral zones appear (Plate II), and their latitudes vary with the magnetic and electric field strengths as predicted by the theory. The current system is in essential agreement with the theory. There exist, however, some differences between nature and model, which will be discussed now.

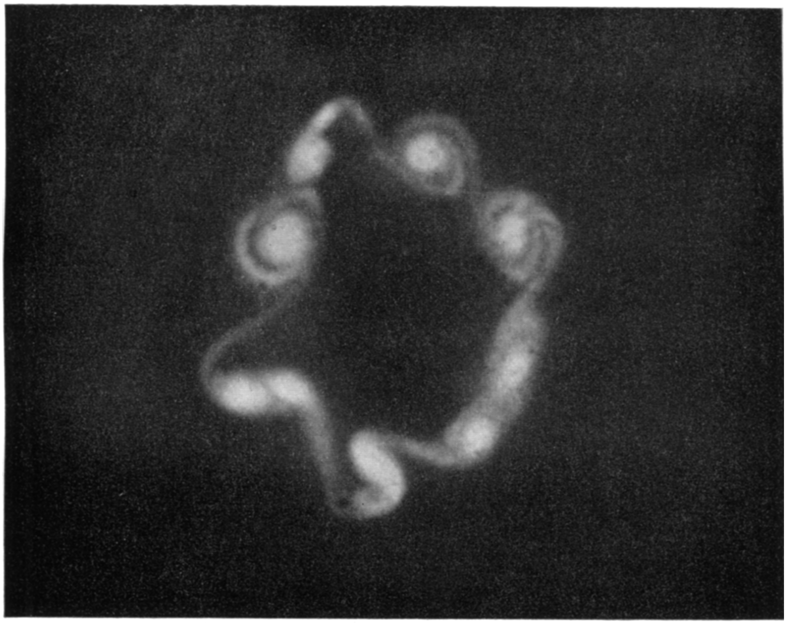
According to the similarity laws of gaseous discharges with different linear dimensions the magnetic and electric field strengths must be increased by the same factor as the linear dimensions are decreased. Since the earth is about 10^8 times greater than the terrella, the magnetic field of the terrella should be 6×10^7 gauss at the poles, which is impossible to obtain. However, it can be shown (Block [9]), that the drift orbits of the electrons and ions are properly scaled down in the model experiments, although the radius of curvature of the circular motion superimposed on the drift motion is comparatively much larger in the model than in nature (Fig. 2). It is probable, however, that this incorrect scaling down of the radius of curvature is of minor importance. The main reason for this is, that as soon as the magnetic field has reached the value where auroral rings appear, the general character of the discharge is unchanged even if the magnetic field is increased by a factor 10.

Eq. (1) is certainly fulfilled in the glow discharge but not in the dark discharge. In both cases, however, the general character of the discharge agrees with the theory, and this favours the opinion, that even if sufficiently many charged particles are available, the charge separation will not be too great.

The pressure in the dark discharge is a few times 10^{-4} mm, which means that the mean free path of the electrons is longer than the linear dimensions of the forbidden space by a factor 3 or so. In nature the corresponding



(a)



(b)

Plate I. Webster's hollow electron beam, (a) 1 cm from the cathode, (b) 8·5 cm from the cathode (from H. F. Webster[5]).

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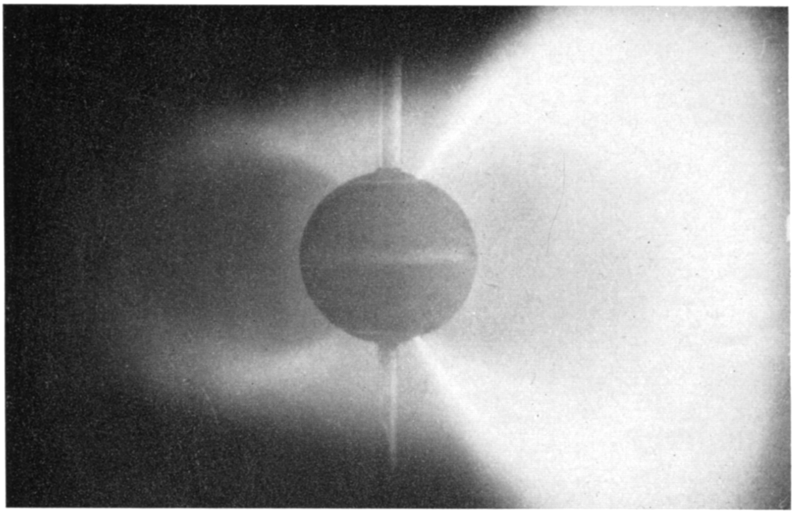
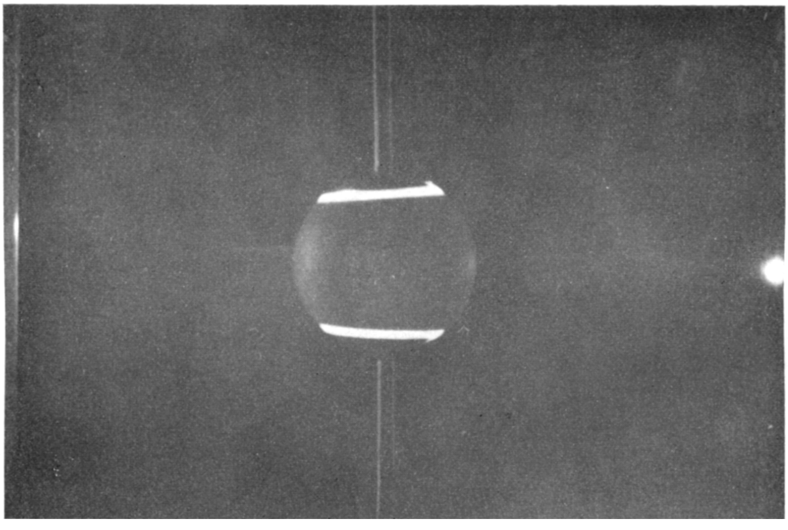


(*a*)



(*b*)

Plate II. (*a*) The self-sustained glow discharge.
(*b*) The non-self-sustained dark discharge.

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factor is several powers of 10. In the glow discharge, however, the mean free path of the electrons is smaller than the forbidden space. Thus, the dark discharge is more like nature as far as the pressure is concerned, but considering the number of charged particles—Eq. (1)—the glow discharge is a far better model of nature.

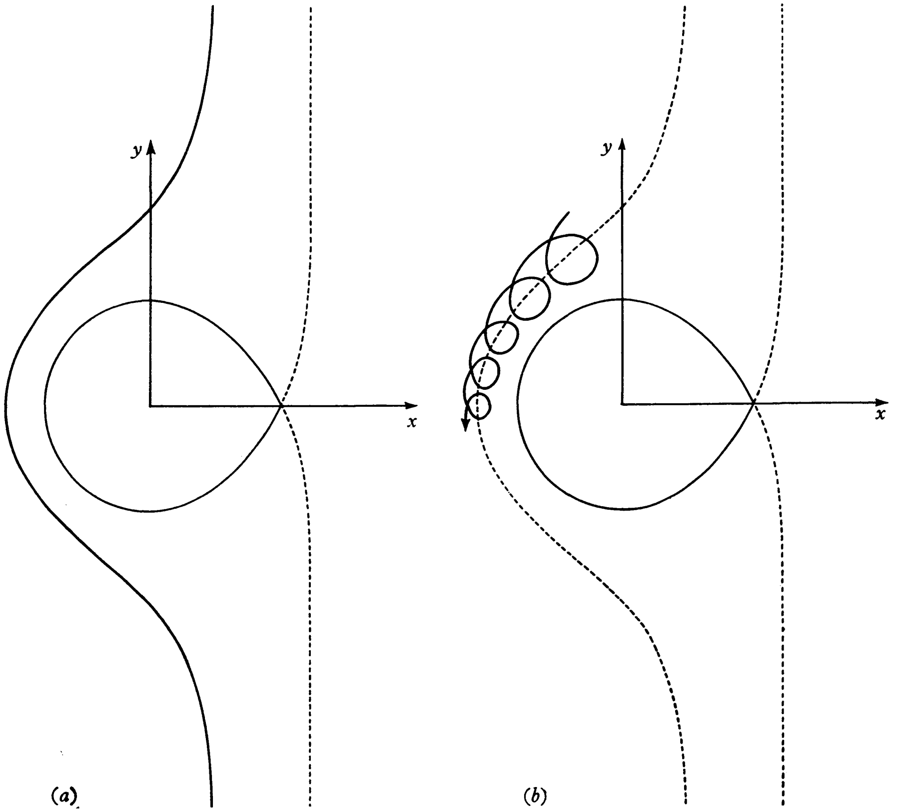

Fig. 2. Comparison of electron orbits in nature (*a*), and in the model (*b*).

The most serious disagreement between nature and model is probably that the ions can move rather freely in the model without being affected appreciably by the magnetic field of the terrella. This means, that the positive space charge accumulation predicted by the theory on the day side of the terrella will not take place, so the ion current in the auroral zone will be directed parallel to the electric field instead of from the day side towards the night side. This is also observed in the model.

It is observed in the experiment, that as soon as the magnetic field has become so strong that auroral rings are formed, a noise suddenly appears.

The spectrum of the noise extends at least from some 10 kc/s up to more than 5 Mc/s. This noise may be due to something like the previously mentioned plasmoids or bunches of charged particles.

The complicated pattern of aurorae with many different auroral forms may very well indicate the existence of some sort of particle bunching in space outside the earth. The particles in the beam from the sun may form bunches, expanding and stretching along the magnetic lines of force with one end appearing as aurora in the ionosphere. The motion of the bunches across the magnetic field may account for the rapidly moving auroral forms, so frequently observed in nature.

4. SOME SPECIAL PROBLEMS

(a) *The density of the beam*

We will now consider the particle density of the beam from the sun. There are several reasons to believe that the density of the beam could not exceed about 10 particles/cm^3 at the earth's orbit (Alfvén [10]), and a lower limit of the density seems to be 10^{-1} cm^{-3} for an average magnetic storm. There are three independent ways of obtaining a lower limit. The highest of these three different limits thus obtained, must certainly be chosen as a real lower limit. We may consider

(i) the currents in the auroral zones,

(ii) the luminosity of the aurorae,

(iii) the time rate of producing the magnetic energy of a storm disturbance.

These considerations, in particular that of the luminosity of aurorae, are certainly very uncertain.

The currents in the auroral zones must be closed by currents along the magnetic field lines from the equatorial plane. The auroral particles are picked up from the beam over a cross-section which may be considered as a rectangle of area A with one side equal to the size of the forbidden zone, 10^{10} cm, and the other side may be 10^9 cm, or a little more than one earth radius. Then the current will be

$nevA = I \approx 10^6$ amps,

n = lower limit of number density of charged particles in the beam,

$e = 1{\cdot}6 \times 10^{-19}$ coulombs,

$v = 2 \times 10^8$ cm/s,

$A = 10^{19}$ cm^2.

This gives $n = 3 \times 10^{-3}$ cm^{-3}.

Thus the number of particles impinging in the auroral zones is

$$N = nvA = 3 \times 10^{-3} \times 2 \times 10^{8} \times 10^{19} = 6 \times 10^{24} \text{ particles/sec.}$$

If the total area of the auroral zones is equal to two 1000 km wide, ring-shaped zones at a mean latitude of 23° from the poles or

$$\pi \times 6{\cdot}4 \times 10^{8} \times \sin 23^\circ \times 10^{8} = 10^{17} \text{ cm}^2,$$

we get about 10^8 particles/cm² sec.

If 10^{-3} of the energy of all these particles is converted into visible light, it would be equivalent to 10^9–10^{10} photons of oxygen green lines ($\lambda = 5577$ Å) per cm² and sec, covering the whole area of the auroral zones at the same time. This corresponds to auroral international brightness I–II (Seaton [11]). Thus, this number of particles is sufficient to produce the visible light of aurorae.

The magnetic energy of the S_D-field must be taken from the kinetic energy of the beam. Across an area A, perpendicular to the motion of the beam, there is passing a kinetic energy/sec amounting to

$$nAv \, . \frac{mv^2}{2} = P.$$

Assuming the magnetic energy to be due to a dipole M, parallel to the earth's dipole, at a distance r from the earth, so that the magnetic disturbance field on the earth is ΔB, we get the mutual energy of the two dipoles (the energy necessary for moving M from infinity)

$$W_m = \Delta B \, . \, M_0,$$

where M_0 = the earth's dipole moment.

The time T to produce this energy is obviously

$$T = \frac{W_m}{P} = \frac{\Delta B \, . \, M_0}{nA \, . \, \frac{m}{2} \, . \, v^3},$$

or

$$nT = 5 \Delta B \text{ sec/cm}^3$$

if the above-mentioned values of A and v are used, if m = proton mass and if ΔB is measured in gammas.

Applying this formula to a sudden commencement with $\Delta B = 10\gamma$, we get, e.g. $n = 10^{-1}$ particles/cm³ and $T = 500$ sec, and for the main phase with $\Delta B = 100\gamma$ and $n = 10^{-1}$, T becomes 5000 sec.

It can thus be concluded, that a particle density in the beam of 0·1 per cc is sufficient for a moderate storm.

(b) The energy of the auroral particles

The energy of the particles impinging in the auroral zones may be expected to be of the order of eV, where V is the voltage difference across the forbidden space in the equatorial plane. This is probably about 100 kV in nature, and in the model it is a few kV. The energy of the auroral particles in the model has been measured by putting a spherical grid around the terrella and supplying a variable voltage between the grid and the terrella (Fig. 3). When the terrella is so negative with respect to

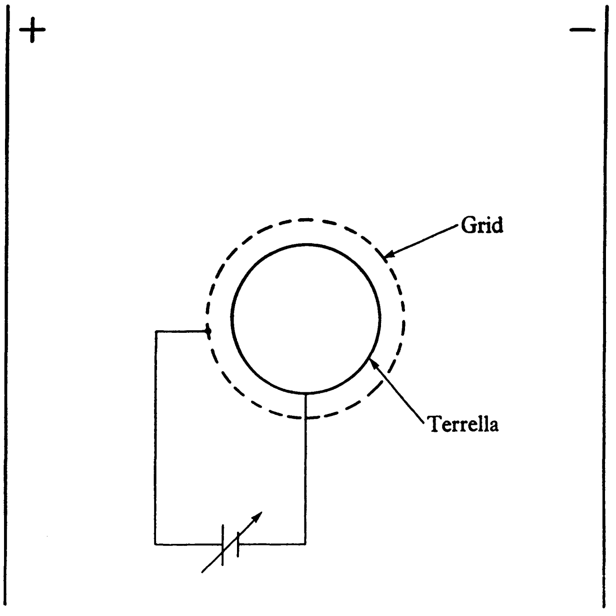

Fig. 3. Arrangement for measuring the energy of the particles impinging on the terrella.

the grid, that the voltage difference is about half of the voltage across the forbidden space, the ionization suddenly increases very much outside the auroral rings of the terrella. This must be due to Barkhausen oscillations of the electrons in and out through the grid. If the voltage between the two condenser plates is increased a little, the electrons gain more energy so that they can reach the terrella and be absorbed there. Thus, the intense ionization vanishes again.

(c) The eccentricity of the auroral zones

As seen from Plate II the experiments give eccentric auroral zones. The direction of the eccentricity indicates the direction of the electric field. By observing the eccentricity during a particular magnetic storm, it should

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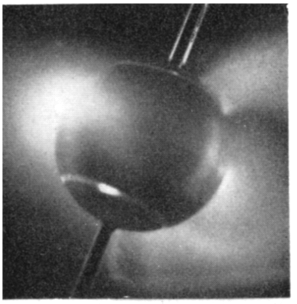
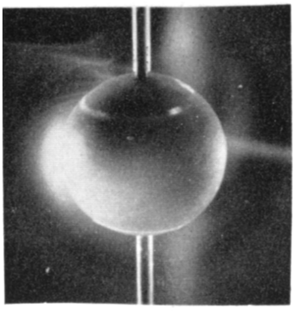


(*a*)



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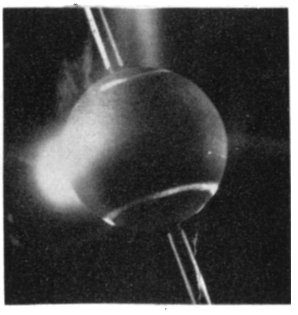

(*c*)

Plate III. The dipole axis of the terrella is tilted 23·5° at different directions, corresponding to different seasons of the year: (*a*) September, (*b*) December, (*c*) March.

(*facing p.* 320)

thus be possible to derive the direction of the electric field causing this particular storm.

We define the eccentricity as

$$\epsilon = 1 - \frac{\text{Minimum polar distance}}{\text{Maximum polar distance}}.$$

The experiment gives $\epsilon_{\text{exp}} = 0{\cdot}10$–$0{\cdot}20$.
The theory gives $\epsilon_{\text{th}} = 0{\cdot}29$.
The difference may be explained by space charges, which change the shape of the forbidden space in the equatorial plane.

The eccentricity of the auroral zones should cause a double periodicity in the diurnal variation of the vertical component, ΔZ, of the S_D-field at magnetic observatories situated at auroral latitudes (Alfvén [1], p. 197). Consulting Vestine *et al.* [12] one finds, that such a double periodicity is detected at stations between 70·8° N (Juliannehaab) and at least 67·1° N (Tromsö) or possibly 64·5° N (College, Fairbanks). This means that the eccentricity of the northern auroral zone may be between 0·16 and 0·25.

(*d*) *Diurnal and seasonal variation of auroral frequency*

It is seen from Plate II (*b*), that all points in the auroral zones are equally illuminated in the experiment. However, this is only true when the dipole axis of the terrella is exactly perpendicular to the electric field and the motion of the beam. If the dipole axis is tilted only a few degrees, the auroral zones are divided into strongly luminous spots, separated from each other by areas of weak luminosity. This is certainly in better agreement with nature.

By tilting the dipole axis 23·5° at different directions, corresponding to different seasons, the photos in Plate III have been obtained. They are all taken from the 'night side' of the terrella, so the 'morning side' is to the right. It is seen that at the solstices, there are two bright spots, one before and one after midnight. Thus, we should have two maxima of auroral frequency during the winter nights. At the equinox in September, on the other hand, we have only one bright spot at about midnight in the southern auroral zone. In March there is only one bright spot in the northern auroral zone.

It is well known from observations in nature (see, e.g. Vegard [13]) that there are two maxima of auroral frequency, one before and one after midnight. But this is an average over the whole year, and it might very well be only one maximum in some seasons. In fact, the observations by Carlheim-Gyllenskiöld [14] during the first polar year 1882–3 indicate that there occurred only one maximum at midnight at the equinoxes. The diagrams

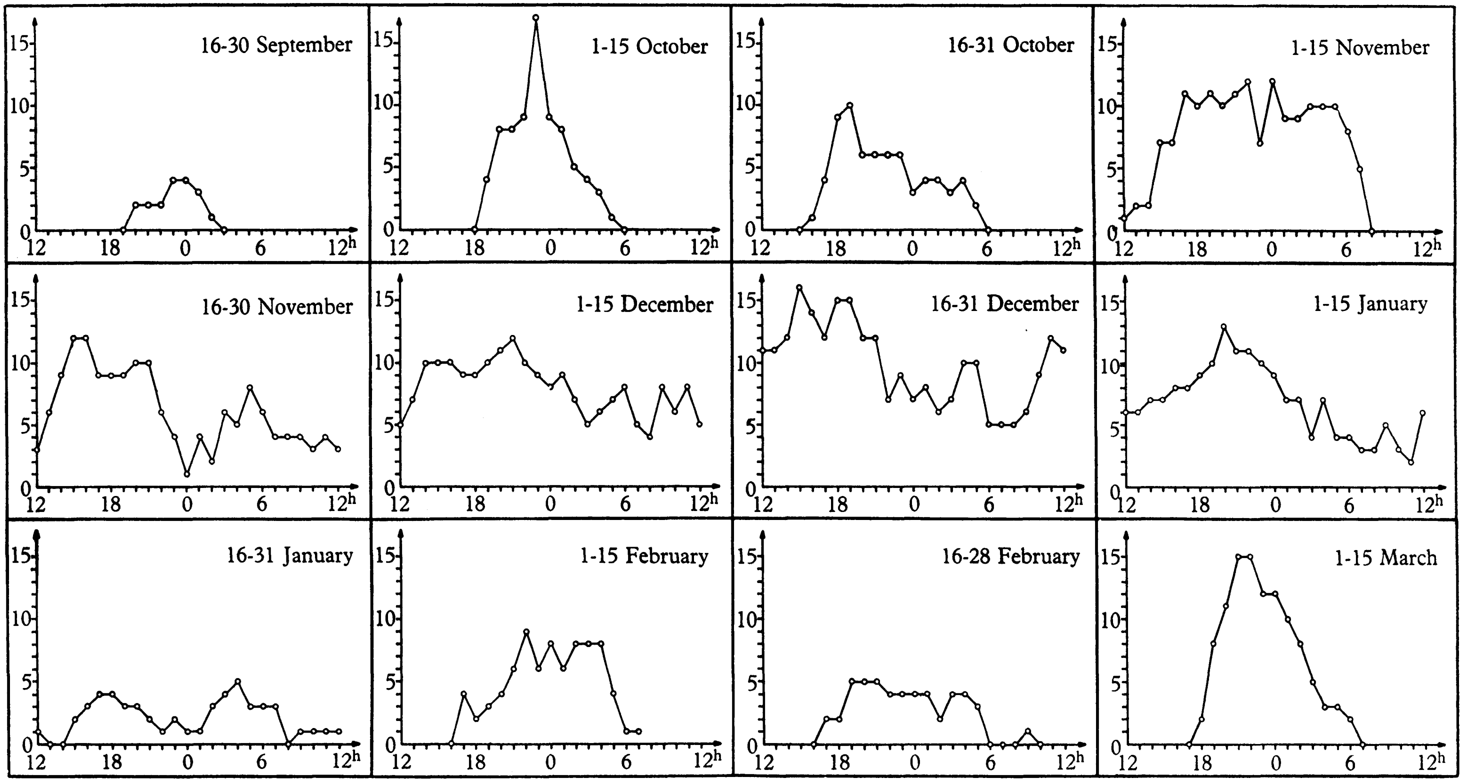

Fig. 4. Hourly total number of aurorae observed each half month during the winter 1882–3 by Carlheim-Gyllensköld[14] at Cap Thordsen, Spitzbergen.

in Fig. 4 show the hourly total number of aurorae observed by Carlheim-Gyllenskiöld during each half month of the winter 1882–3.

In the model experiments it is also observed, that the current of the discharge at the 'equinoxes' exceeds the current at the 'solstices' by about 25 %. This may have something to do with the well-known fact that magnetic disturbances are more frequent at the equinoxes than at the solstices.

It is astonishing, that the agreement between nature and the model is so good, although it is not yet proved, that some of the agreements are not more or less accidental.

In Table 1 a summary is given of some differences and similarities between nature and the model discharges.

Table 1. *Properties of discharges in nature and in model experiments*

	Nature	Glow discharge	Dark discharge
$en > \mathrm{div}\, \epsilon_0 \boldsymbol{E}$	Yes	Yes	No
Mean free path > L = size of forbidden zone	Yes	No	Yes
Plasma instabilities	Many auroral forms indicate instabilities	Noise observed	Noise observed
Ion current in auroral zones	Perpendicular to el. field	Unknown	Parallel to el. field
ρ/L = trochoidal radius of curvature comp. with size of forb. zone	10^{-4}	10^{-2}	5×10^{-2}
Eccentricity	0·16–0·25	0·10–0·15	0·15–0·20
Seasonal var. of magn. activity	Magn. dist. more frequent at equinoxes	Discharge current at 'equinoxes' 25 % greater than at 'solstices'	
Seasonal and diurnal var. of aurorae	Two max. during winter night, possibly one in spring and autumn	Unknown	Two max. in winter, one in spring, no def. in autumn

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Discussion

Singer: In our models, when we try to explain such complicated phenomena as magnetic storms and aurorae, we start with an idealized situation. That means that we take some observational facts as relevant and reject others. The problem is that we all differ on what is relevant or not relevant. As an example, the electric field theory considers the diurnal variations of importance. From my point of view I consider the fact that the sudden commencement currents flow mostly in the atmosphere as very relevant, but Ferraro does not. I also consider very significant the fact that the sudden commencement is preceded by a reverse commencement. This is particularly shown in one of the slides which Ferraro demonstrated.

Now, I want to ask Dr Block: for what gas densities around the earth does your model work?

Block: I think that it works at an extremely low density but there must be an upper limit, i.e. that the mean free path cannot be orders of magnitude smaller than the distance for the beam to proceed as far as to the earth. It would lose too much energy by collisions with the interplanetary gas. Very close to the earth the density may be higher.

Singer: I believe that the initial phase of a magnetic storm is explained by the ring-current at 30 earth-radii from the earth, according to the electric field theory.

Block: Yes, partly. But I think we must also take into account the jet streams in the ionosphere.

Singer: How does one explain the delay between the sudden commencement and the main phase in the electric field theory?

Block: This is not worked out very much in detail. There are certain differential equations which are very difficult to solve, but some theoretical calculations indicate that the delay should not be smaller than about 10 min; this estimate is very rough, of course.

Singer: It should be a few hours.

Block: Yes, but this is not very well explained.

Alfvén: I think that Block's experiments and the whole theory in its present development concentrates on the main phase; concerning the initial phase there are some recent attempts to study this phenomenon. In the electric field theory the main phase is caused by the formation of space charges at the boundary of a forbidden region. The energy of the incoming particles is taken from the electric field (Fig. 1). But then there is also, as shown in Fig. 1, a current produced at a very large distance of about 30 radii which is due to the braking of the beam when it comes into the earth's magnetic field. Here the earth's magnetic field equals the interplanetary field and the drift motion of the particles is affected by inertia forces. This would correspond to an inner auroral zone at a polar distance of about 5° whereas the outer auroral zone is at 23°. It would be very important to look for the existence of this inner auroral zone. I was very glad to hear at the arctic conference here in Stockholm in May that research in the Soviet Union by Dr Nikolski has given very good evidence for the existence of such a zone.

The effect of the application of an electric field in the region around the earth is not confined to the phenomena we have studied all of which derive from the properties of the beam. The electric field should also set into motion the ions which exist already in the neighbourhood of the earth. This is a point where Singer's question is very important. The motion of the already existing ions should produce currents in the upper atmosphere. We should also study the currents produced by the electric field directly in the upper atmosphere.

Ferraro: I should like to make a remark to Dr Block about the model experiments. Chapman has drawn the attention to what is the right scale when moving from nature to laboratory. Professor Cowling drew attention to this also yesterday.

Now, as regards the *R*-circle (see Fig. 1) which is supposed to produce the first phase, I am not quite sure I understand how this comes about. One thing that puzzled me was the effect that the displacement of the positive ions in the regions where the earth's magnetic field and the interplanetary field are equal was greater than that of the electrons. Is that a line current?

Alfvén: No. This is a space current and it comes out straightforward from the assumptions which Block stated very clearly. You just calculate the motions of electrons and ions in an electric field and a combined magnetic field of the earth and interplanetary space.

Ferraro: Could you tell me quite briefly how it comes about that the displacement of positive ions is greater than that of the electrons? I should have thought that in the regions where the interplanetary and terrestrial fields are equal, the gradient is very near to zero.

Block: I think Dr Ferraro has misunderstood us here. The gradient of the magnetic field is not zero because we assume that the interplanetary and terrestrial field have the same direction. The deflexion of the particles is caused by inertia forces.

Ferraro: I thought that the gradient in the earth's magnetic field was responsible for the spiralling and streaming motions of the electrons around the earth so as to produce a westward current. But does not this produce an eastward current?

Alfvén: This is an inertia effect of the ions. If you have an ion which drifts into an increasing magnetic field you brake the translational velocity and this produces a drift.

Ferraro: Then somewhere you get a reverse of that drift?

Alfvén: Yes.

Ferraro: Does not this cause a discontinuity?

Alfvén: This is due to the braking of the velocity. We can take it as a transformation of kinetic energy into field energy. It is necessary to have such a displacement; it comes out through straightforward calculations.

Lovell: In connexion with Dr Block's simulation of the diurnal effects a comment on the recent radio echo results may be of interest. In this work the radio echoes scattered from the ionized auroral regions are recorded, and it is

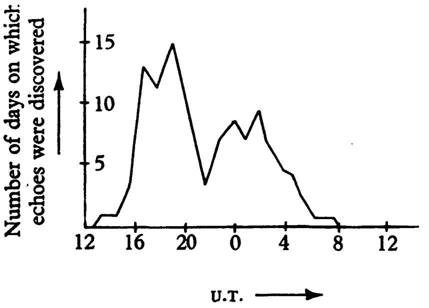

Fig. 5. Diurnal variation in the rate of occurrence of aurorae as determined by the radio echo technique.

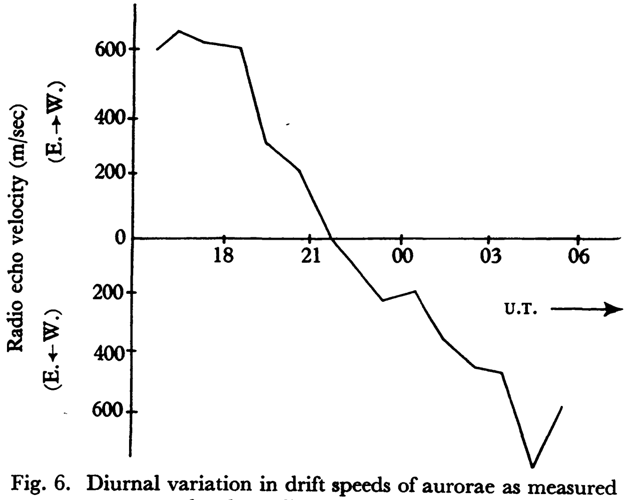

Fig. 6. Diurnal variation in drift speeds of aurorae as measured by the radio echo technique.

possible to determine the range, speed of drift movements and the nature of the reflecting agency independent of daylight or sky conditions. The diurnal variation is given in Fig. 5 which shows two main peaks at about 18^h and 02^h with a minimum at 22^h. The most significant features of this minimum may be listed as follows:

1. The minimum is associated with a change in drift motions of the reflecting regions as shown in Fig. 6. At the first maximum the drifts reach 600 m/sec

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east to west; at the minimum the drift is zero and reaches over 600 m/sec west to east at the time of the second maximum.

2. The variation of the ΔV component of the earth's magnetic field follows this drift curve closely.

3. There is a marked change in the type of radio echoes observed, those in the early maximum being mainly diffuse, whereas after the minimum the echo structure is predominantly discrete. In one notable case observed on 25/26 September 1951 these changes in echo structure were closely correlated with a change in the appearance of a visual aurora from a stable arc to pulsating rays and diffuse patches.

4. The drift motions determined from radio star scintillation observations are normally associated with the F-region and show reversals in direction at midnight. When observed in the auroral zone these drifts show a partial reversal in direction at the time of the minimum in Fig. 5.

These data have been obtained at Jodrell Bank (geomagnetic latitude 56°) during the years of sunspot minimum (1949–54), the reflecting regions being about 50 km northwest of the station. Some of this information has been published by Bullough, K. and Kaiser, T. R. (*J. Atmos. Terr. Phys.* **5**, 189, 1954, and **6**, 198, 1955).

Block: Do the aurorae move across the sky in a certain direction?

Lovell: We do not know if the visible aurorae moves. What we detect is the ionization in the aurorae and this shows a drift and a reversal.

Lowes: Do you have to have the interplanetary field in the same direction as the geomagnetic field in order that the mechanism shall work? Is it possible for it to work with an interplanetary magnetic field in the opposite direction?

Block: The interplanetary magnetic field is only necessary for the theory of the initial phase. For the main phase the interplanetary field is not essential. What is essential is that an electric field exists, directed from the evening side towards the morning side of the earth.

Cowling: Does the main phase of a magnetic storm persist only while the ionized stream is flowing continuously past the earth?

Block: For the main phase it is only essential that an electric field exists. The direction of this field is determined by the diurnal variation of the aurorae and associated magnetic disturbances. This direction can be explained by a beam moving from the sun in an interplanetary magnetic field of the same direction as that of the geomagnetic field. If you can produce an electric field in some other way it is all right.

Cowling: In such a case the stream must persist for about 3 or 4 days?

Block: Yes.

Alfvén: If a discharge of this type stops at once there are after effects. If you switch off the electric field the particles will no longer move in eccentric orbits but in circular orbits around the earth. The eccentricity of the forbidden region is produced by the electric field. If you take away the electric field you have still ions and electrons present and they will drift around in circles until they are absorbed by some mechanism. But at the same moment as you switch off the electric field the eccentricity of these orbits, and also the eccentricitv of the auroral zone, will become zero.

Cowling: Will you at the same time have essentially the same ring-current?

Alfvén: No, the ring-current in this case is due to electrons moving in trochodial orbits. It is well known from experiments that such a ring-current is stable and all the objections against the stability of the currents in Chapman–Ferraro's theory are inapplicable here.

Singer: How do you explain the acceleration of the protons impinging on the auroral zones?

Block: One possible explanation is as follows. The earth may be considered as a probe in a gaseous discharge. It will be charged by electrons to a negative potential approximately equal to that at the point *A* in Fig. 1 at the boundary of the forbidden space around the earth in the equatorial plane. Then, the resulting potential differences between the other points of the forbidden space boundary and the earth will accelerate the protons.

Other mechanisms are also conceivable, e.g. plasma instabilities and bunching of protons in the equatorial plane. The electric fields of these positively charged bunches may accelerate protons towards the auroral zones. This may perhaps explain the highly unstable and fluctuating auroral forms.