ON THE IMPORTANCE OF ELECTRIC FIELDS IN THE MAGNETOSPHERE AND INTERPLANETARY SPACE

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1. Introduction

The motion of a charged particle in space is determined by the electro-magnetic tensor (and the gravitational field). The magnetic components of this tensor are being mapped as a result of space research, but very few direct measurements of the electric field have yet been made. It is important to stress that no real understanding of the electro-magnetic conditions in interplanetary space and in the magnetosphere is possible unless we know the electric field.

In fact, we are in a position which is similar to that of the geographers a few hundred years ago. It was easy for them to determine the latitude but very difficult to determine the longitude of a place. Evidently, no reliable map could be constructed unless both the latitudes and the longitudes were known. In a similar way we cannot understand the properties of the magnetosphere unless we know both the magnetic and the electric field.

As very few measurements of the electric field have yet been made we have to confine ourselves to a survey of current theories.

2. Interplanetary Space

A. GENERAL PROPERTIES OF THE INTERPLANETARY MEDIUM

Of all the theories of interplanetary space which were proposed before space measurements could be made there is only one which has survived the encounter with observational facts. With the behaviour of cometary tails as a starting-point BIERMANN (1951, 1953) concluded that the sun continuously emits a 'Korpuskularstrahlung' (corpuscular radiation) in all directions, and he also gave the equations which must regulate this radiation. Space-probe measurements have confirmed the correctness of Biermann's theory in a striking way, although the phenomenon now is referred to as 'solar wind' by PARKER (1960) and others.

Biermann's picture has therefore replaced the older picture according to which the sun emitted plasma only from active regions. Based on this older view CHAPMAN and FERRARO (1931, 1932, 1933, 1940) worked out a theory of magnetic storms, which dominated the discussion during a quarter of a century. An essential feature of this theory was that the plasma emitted from the sun should be non-magnetized, and that the electric field in the region reached by the plasma should be zero.

The possible importance of a magnetized interplanetary medium was pointed out

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in 1939 in a theory according to which the magnetization of the medium and hence its electric field should be of essential importance (ALFVÉN, 1939, 1940).

B. CO-ROTATION

One consequence of electromagnetic forces in the interplanetary medium was a possible co-rotation with the sun. This is of course only an application to the conditions around the sun of the Ferraro theorem of iso-rotation.

Cosmic-ray measurements have confirmed that in general the cosmic radiation does co-rotate. This has been demonstrated especially through the work of SANDSTRÖM and his group in Uppsala, and is discussed in detail in his recent book on Cosmic Rays (1965). However, space measurements show that the interplanetary plasma moves radially and seems not to take part in the solar rotation. A possible and very ingenious solution of this dilemma has been suggested by AHLUWALIA and DESSLER (1962), who show that in the presence of a spiral-shaped magnetic field, a Biermann radiation which does not take part in the solar rotation is reconcilable with a Sandström co-rotation of cosmic radiation.

C. THE SUN'S GENERAL MAGNETIC FIELD

The electromagnetic conditions in interplanetary space are intimately connected with the electromagnetic conditions of the sun. Of special importance is the general magnetic field of the sun. When the electromagnetic conditions in interplanetary space were first taken up to discussion, the Mount Wilson astronomers claimed that their Zeeman-effect measurements showed a dipole field on the sun with a polar strength of 50 gauss (HALE *et al.*, 1918) and the same polarity as the earth's magnetic field. During the last decade they have claimed that the general magnetic field is of the order of 1 gauss (BABCOCK and BABCOCK, 1955), and that it varies with time, so that sometimes it is parallel and sometimes antiparallel to the earth's field.

It is possible to estimate the solar magnetic field in a completely different way. For reasons which shall not be repeated here, it is likely that the sunspots are caused by disturbances originating in the solar core and travelling outwards as hydromagnetic waves along the field lines of the sun's general magnetic field (ALFVÉN, 1945, 1950). The speed of progression of the sunspot belts from high latitudes towards the equator allows us to estimate the general magnetic field. This method gives a value of about 10 gauss. The direction of the field cannot be determined.

Serious objections have been raised against the Mount Wilson reports about the variable solar magnetic field. Already long ago COWLING (1945) had shown that the general magnetic field of a rigid body with the size and the conductivity of the sun should have a time constant of billions of years. Although the fact that the sun is fluid does not make this conclusion directly applicable, it is obvious that a rapidly varying general field must be a surface phenomenon. However, it seems very doubtful whether the Mount Wilson field distribution is at all reconcilable with the Maxwell equations (ALFVÉN, 1965). Further the reliability of the Zeeman-effect measurements has been questioned also on the ground that the solar field may have an unresolved fine structure, which may give an incorrect, apparent mean of the magnetic field (ALFVÉN and LEHNERT, 1956; ALFVÉN, 1965).

A clarification of the contradictory results seems now to be on its way thanks to the new magnetographic technique developed by Severny at the Crimean observatory. SEVERNY (1965) has discovered a fine structure of the solar magnetic field, and he has demonstrated the existence of strong magnetic field regions of the size of one or a few seconds of arc.

Using the Severny technique, STENFLO (1966) has systematically analyzed the influence of the slit size on the magnetograph readings. The result is seen in Figure 1.

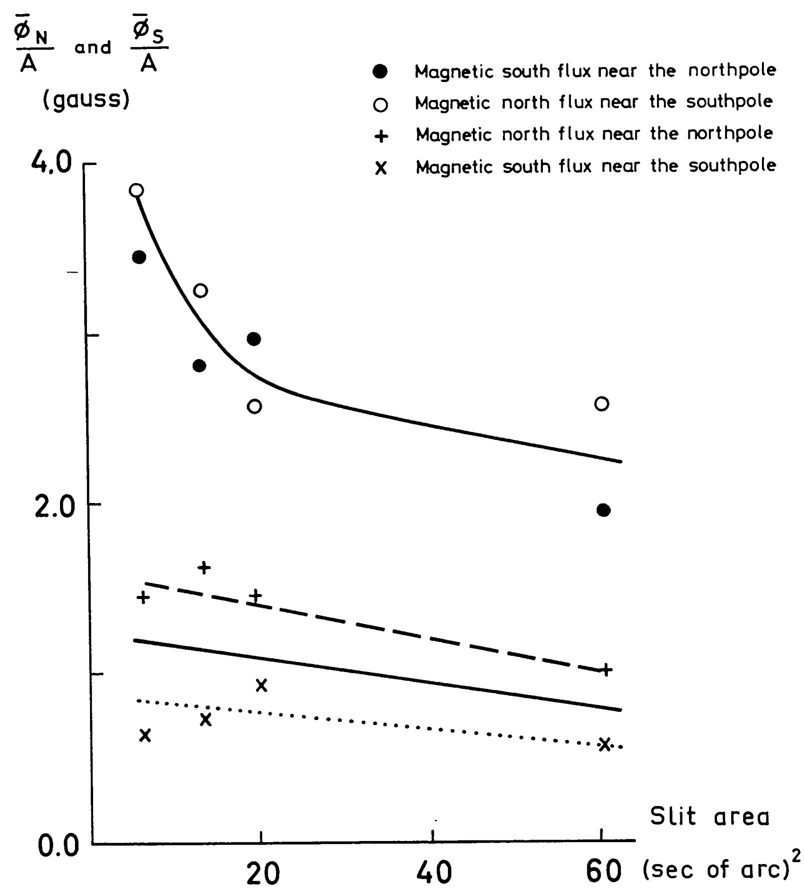

Fig. 1. Variation of the apparent solar magnetic field when the size of the magnetograph slit is varied.

When the slit was narrowed so that the field of observation decreased from 60 to 7 (sec of arc)^2, the apparent North pole magnetic field near the heliographic North pole and the South pole magnetic field near the heliographic South pole were not affected very much. On the other hand, the apparent South magnetic field at the heliographic North pole and the North magnetic field near the South pole increased very much. The conclusions from these results are:

(1) The Mount Wilson measurements of the general magnetic field, most of which are made with a slit which is much larger than the largest slit used by Stenflo, are not reliable.

(2) The sun has a general field with a pole strength in excess of 5 gauss. The direction of the field is the same as the terrestrial field.

The results are preliminary and need confirmation. A systematic investigation of the solar field with a slit as small as 1 $\sec^2$ may be necessary before the sun's general magnetic field can be determined with certainty.

An attempt to correlate solar magnetism and the electromagnetic conditions in interplanetary space has recently been made by NESS and WILCOX (1966), but a better understanding of the solar magnetic fields is essential for further progress in this direction.

D. ELECTRIC FIELD AND MAGNETIC FLUX

Let us apply the second Maxwell equation in the form

$$\oint E_s \, \mathrm{d}s = -\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

to a curve given by the orbit of the earth. Then ϕ means the magnetic flux through the orbit of the earth, and if the line element $\mathrm{d}s$ points in the direction of the earth's motion, E_s means the electric field in the same direction.

Hence, a determination of the electric field component parallel to the orbital velocity of the earth is important for clarifying the magnetic-flux conditions in interplanetary space.

If we *assume* that in interplanetary space the magnetic field is frozen-in in the plasma (but it is not quite clear whether this assumption is justified) we have

$$E_s = v_r \times B_z$$

where v_r is the velocity of the plasma, which is radial, and B_z the magnetic component perpendicular to the ecliptic plane. The flux transported per unit time is

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = \oint E_s \, \mathrm{d}s \, .$$

With $R_{♁} = 1.5 \times 10^{13}$ cm, and the typical values of v_r and B_z being $v_r = 3 \times 10^7$ cm/sec and $B_z = 10^{-5}$ gauss, the flux $\Delta\phi$ transported during a time T might be as large as

$$\Delta\phi = 3 \times 10^{16} T \, .$$

(Its actual value, which can be smaller, has to be calculated from the line integral of $v_r B_z$, and this requires more data than available at present.) The value of $\Delta\phi$ should be compared with the total solar flux $\phi_{\odot} = H_p \times \pi R_{\odot}^2 = 1.5 \times 10^{23}$ gauss cm^2, where we have put $H_p = 10$ gauss, which according to what is said above is the most likely value. From this we find that a flux equal to the total solar flux is transported through the earth's orbit in about two months. This illustrates how important measurements of E_s can be for understanding the flux conditions in interplanetary space.

3. Border between Interplanetary Space and Magnetosphere

The phenomena at the border between the interplanetary space and the magnetosphere are of a character fundamentally different from what was predicted by the Chapman-Ferraro theory. There are three reasons for that:

(1) The Chapman-Ferraro plasma was supposed to have the magnetization zero, which means that it behaves as a superconductor. This led to the conclusion that the border of the magnetosphere should separate a field-free plasma region from a plasma-free region with magnetic field.

(2) The density of the Chapman-Ferraro beam was two orders of magnitude too high.

(3) The theory did not predict that, at the border of the magnetosphere, shock-wave phenomena should be of essential importance. The necessity to take account of shock phenomena was first pointed out by SINGER (1957).

The 'electric field theory' (ALFVÉN, 1950, 1955, 1963; BLOCK, 1958a) in which the magnetization of the plasma and its consequent electric fields was essential, avoided the first two difficulties. However, it did not predict the occurrence of shock-waves, hence the need to have it modified considerably before it can describe the transition region.

4. The Magnetosphere

A. ELECTRIC FIELD IN THE MAGNETOSPHERE

The magnetic field in the magnetosphere is reasonably well mapped, at least over large parts of it, but the electric field is almost completely unknown. An urgent task for the investigation of the magnetosphere is to explore the electric field.

It has been claimed by some authors that in the magnetosphere the electric field $E_{//}$ parallel to the magnetic field must be zero, and famous theories have even been built up with this as a starting-point. The conclusion $E_{//}=0$ would have been correct if the density in the magnetosphere had been so high that the mean free path had been small compared to the linear dimensions, but at least in the outer magnetosphere this is not the case. The concept of conductivity has no meaning when the mean free path is as large as it is in the outer magnetosphere (ALFVÉN and FÄLTHAMMAR, 1963, p. 191).

The magnetic field in the magnetosphere is a mirror field with a very high mirror ratio, several hundred for the outer region. PERSSON (1963, 1966) has treated a plasma in a mirror field and has shown that if the mean free path is long compared to the linear dimensions, the electric field $E_{//}$ can be zero only if the pitch-angle distributions of the electrons and of the ions are equal. This means that if a certain number of electrons have pitch angles between α and $\alpha + d\alpha$ at a given point, there must be the same number of ions in the same pitch-angle interval. The condition is independent of the energy, so that it does not matter whether the electrons are compensated by low- or high-energy ions, provided that the pitch-angle distributions for ions and elect trons are the same. If the pitch-angle distributions are different, an electric field mus be produced which may be static or oscillatory.

Hence, we see that $E_{//}=0$ can be established only under certain special conditions. (A Maxwellian distribution or, more generally, any isotropic distribution of both ion and electron velocities does give $E_{//}=0$.)

A laboratory experiment has been started in order to study the production of electric fields in a plasma in a mirror field. A preliminary report is being published by ANGERTH, EHRENSVÄRD, and PERSSON (1966). In terrella experiments by BLOCK (1955, 1958b) and by DANIELSSON and LINDBERG (1964a, b) electric fields near the terrella are often observed, but it is not quite clear to what extent these results are applicable to space conditions.

The first observational evidence for the existence of electric fields in the magnetosphere has been obtained by JOHANSEN and OMHOLT (1963). From measurements of the Doppler effect of the Hα line during aurorae, they were able to draw some conclusions about the pitch-angle distribution of the incident protons. In order to explain the distribution it seems necessary to assume that there is an electric field somewhat above the ionosphere, which is associated with a voltage drop of the order of 10000 volts. Some conclusions about electric fields may also be drawn from the Injun results (O'BRIEN, 1964).

It is important to confirm these results by further, similar measurements, but it would be still better if the electric field could be measured in independent ways. This may be an important task for ESRO.

B. MAGNETOSPHERE CURRENT SYSTEM

During magnetic storms there are strong horizontal currents, of the order 10^6 A, in the auroral zones. These currents, usually called the *auroral electrojets*, flow at a height of the order of 100 km and their direction is westward on the morning side

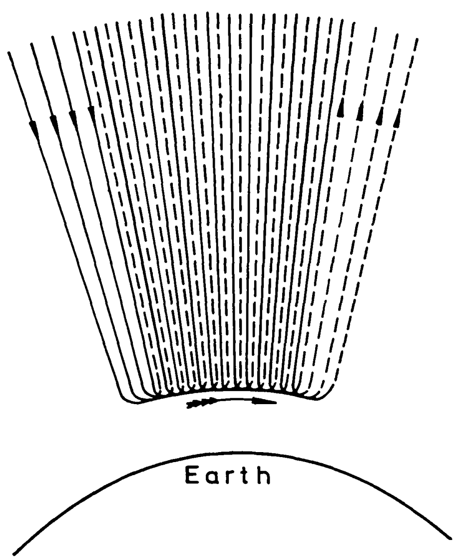

Fig. 2. Birkeland's current system. The horizontal current in the upper ionosphere is part of a current system in the magnetosphere. Currents are flowing to and from the ionosphere along the magnetic field lines.

and eastward on the evening side of the earth. Hence, the currents bring positive charge to the nightside and negative charge to the dayside of the auroral zone.

It is still an open question how the auroral electrojets are closed. In principle they could close either through horizontal currents in the ionosphere or through a current system in the magnetosphere.

The first scientist who studied this problem was BIRKELAND (1908). He suggested that the horizontal currents should close out in space through currents along the magnetic field lines (Figure 2). This was quite natural to him because he thought that both the visual aurora and the horizontal currents associated with it must be produced by phenomena occurring in space outside our atmosphere.

However, this view was not shared by Chapman, who suggested that the whole current system during a magnetic storm should be located in the ionosphere (Figure 3).

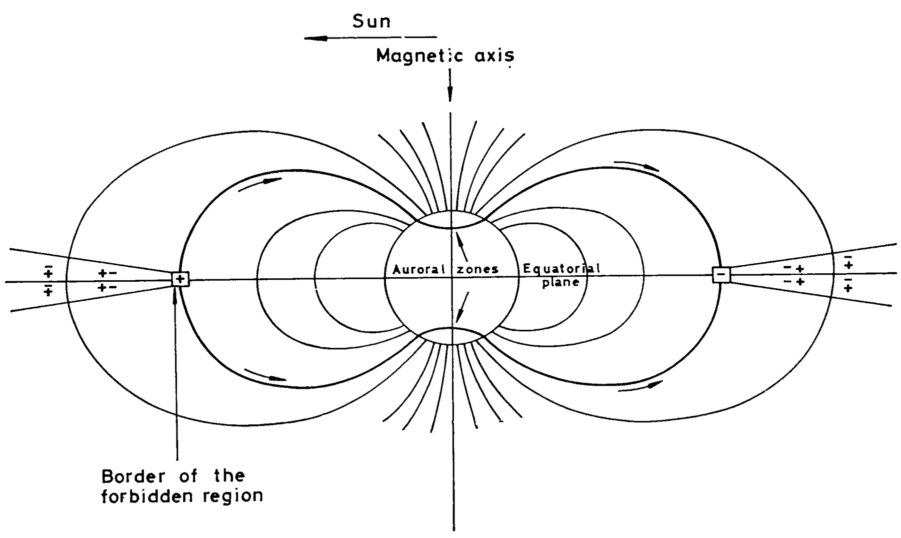

Fig. 3. Current system of the Birkeland type (ALFVÉN, 1940). The driving electromagnetic force for the auroral electrojet is produced in the magnetosphere. Currents flow from the magnetosphere along the magnetic field lines to the auroral zones.

Chapman and Vestine have published a considerable number of pictures of current system derived under this assumption, but they have done very little to verify the assumption on which they are based.

Against Birkeland's current system Chapman objects the following: "On the ground of *a priori* probability of simplicity, therefore, the spherical current-sheet distribution over the polar cap seems preferable to the Birkeland theory. Vestine and Chapman have enforced this conclusion by actual calculation of the magnetic field of a linear current-system, chosen as giving a rough representation of Birkeland's hypotheses, namely a linear current descending vertically from an infinite height down to the auroral zone, on the noon meridian, then dividing equally to right and left to flow along the auroral zone, and flowing vertically upwards again, to infinity, from the point on the midnight meridian where the two parts of the auroral zone current reunite. They find that such a system would not give so strong or so uniform a field, near the centre of the auroral zone, as is observed.

Another important argument against the Birkeland hypothesis of the supply and outflow of the zonal currents is the difficulty in accounting for the existence and maintenance of strong free currents in the empty space around the earth" (quotation from CHAPMAN and BARTELS, 1940, pp. 884–885).

These arguments are now old, and at least today none of them is acceptable. However, to my knowledge they are the *only arguments* ever given against Birkeland's current system. Readers of textbooks or monographs or review articles who always meet the Chapman-Vestine current system, but never hear about the Birkeland picture may be inclined to believe that the dispute about the current system is settled once and for all. This is certainly not the case. There are very good arguments in favour of a Birkeland system of currents closing in the magnetosphere. A recent investigation by BOSTRÖM (1964) about possible mechanisms for producing the auroral electrojets has definite bearing on this question.

Space technology makes it possible now to decide between the Birkeland and the Chapman-Vestine current system. As the question is of decisive importance to our understanding of the electric fields in the magnetosphere and ionosphere, an investigation of how the auroral electrojets close should be placed high on the ESRO priority list.

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