PAPER 32

INTERPLANETARY MAGNETIC FIELD

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ABSTRACT

The magnetic field outside the sun (interplanetary magnetic field) is certainly far from a dipole field. A model of it has recently been suggested (*Tellus*, **8**, 1, 1956). This model is in agreement with cosmic ray and magnetic storm data and reconcilable with the coronal ray structure. Some possibilities to check the model are discussed.

1. INTRODUCTION

The properties of interplanetary space has been only a minor chapter in astrophysics. This is due to the fact that except for the zodiacal light there has been no astronomical phenomenon which we have associated with interplanetary matter. With the rising interest for electromagnetic phenomena in astrophysics, the situation is now changing. As the degree of ionization of the interplanetary gas is high, the condition for magneto-hydrodynamic coupling is well satisfied in interplanetary space (see e.g. Lehnert, p. 54 of this volume). Hence the motion of the interplanetary gas will in general produce electromagnetic phenomena, which may affect the ionosphere (magnetic storms and aurora) and the cosmic radiation (intensity variations). As the motions induce electric fields the electromagnetic state of interplanetary space is a reflexion of the state of gas motion, so that we have a possible way to study the interplanetary 'winds' with electromagnetic methods. We may also say that the electromagnetic state of interplanetary space is regulated by the interplanetary 'meteorological' situation, i.e. the state of gas motion, pressure conditions, etc.

A considerable part of the subjects discussed at this symposium converges into the problems of interplanetary space. A general study of magneto-hydrodynamics is of course fundamental even to this field. Solar physics is important because the interplanetary space may be considered as the extreme outskirts of the solar atmosphere, and its state is certainly regulated to a large extent by the solar activity. Some ionospheric phenomena, especially magnetic storms and aurorae, will certainly be of great value for the understanding of the motions of interplanetary matter. Even if we still disagree fundamentally about the mechanism underlying these phenomena, we do agree that they are caused by the emission of ionized beams or clouds from the sun. Last but not least, the cosmic rays which reach the earth have travelled through interplanetary space and hence may act as probes of its electromagnetic state. If correctly interpreted the variations in primary cosmic radiation will no doubt be an extremely valuable tool in the exploration of interplanetary space.

Hence we find that several different fields of research coalesce and we can trace the contours of a new field of research which may be called *interplanetary meteorology*, concerned with the winds in interplanetary space and hence also with its electromagnetic state. This field is still in a very early stage of its development and quite different ways of approach have been tried—and should be tried.

I intend to discuss a model of the magnetic field in interplanetary space which at the same time is a model of the state of gas motion and hence also of the electric field. This model is essentially the same as has been used long ago in the electric field theory of aurorae and magnetic storms [1] and more recently also in a theory of cosmic ray variations and the local generation of cosmic radiation [2]. The model is only meant to be a first approximation to the real conditions and to represent, at most, an average state.

Its essential properties are shown in Figs. 1, 2 and 3. The model has been discussed in detail in *Tellus* [3].

The background of the model is the following. In the absence of electric currents in space the solar magnetic field should be a dipole field at least at a large distance from the sun. According to Ferraro's theorem it is likely that the magnetic axis coincides with the rotational axis of the sun. The solar activity introduces disturbances of the dipole field, and especially the emission of beams in the equatorial region will tend to 'blow up' the field, so that the lines of force are drawn out. Within a beam the field—if frozen in—should fall as r^{-1}. Outside the beam (or beams) the field recovers but rather slowly, the time constant being of the order of a month or a year [3]. The decrease of the field with increasing solar distance should be more rapid than inside the beam but less rapid than in a dipole field. In the model the field outside the beam is assumed to decrease in average as r^{-2}.

2. PROPERTIES OF THE MODEL

The most important properties of this model are:

1. *The field lines agree with the visual structure of the solar corona.* Independently, Gold [4] has concluded that the fine structure in the corona

should be interpreted as indicating the direction of the magnetic field even near the equator.

2. The field permits *cosmic rays produced by a solar flare* to go almost directly out to the earth. Their path follows a line of force which according to Figs. 1 and 2 may go almost radially. When they arrive to the earth part of them come from the direction of the sun, but there is also a considerable scattering.

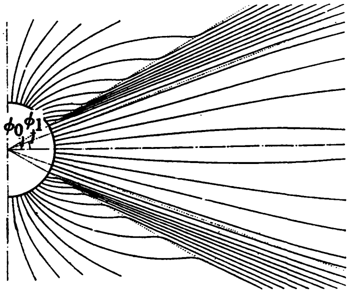

Fig. 1. The solar magnetic field inside a beam (*Tellus*, **8**, 8, 1956).

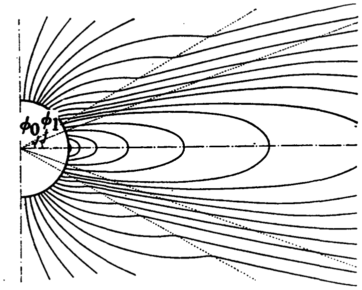

Fig. 2. The solar magnetic field outside a beam (*Tellus*, **8**, 8, 1956).

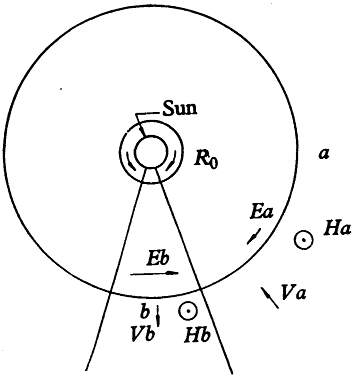

Fig. 3. Field model in the equatorial plane (*Tellus*, **6**, 232, 1954).

3. It gives an *electric field* inside the beam which according to the electric field theory and Malmfors–Block's experiment is essential in order to explain the *magnetic storms and aurorae.*

4. The model also gives a *cosmic ray storm effect and a 27-day variation* of cosmic radiation. These effects will be discussed later.

5. The model is in *apparent conflict* with the Zeeman effect measurements of the photospheric field if these measurements are interpreted in the

conventional way. However, as there is no theory of the Zeeman effect in a turbulent atmosphere, this conflict could not be regarded as serious [5, 6, 7]. On the other hand the model is in agreement with the value of the solar magnetic field derived from the magneto-hydrodynamic theory of sunspots.

3. INFLUENCE OF SOLAR ROTATION

The solar rotation introduces a modification of the model. When ionized matter is ejected in a beam, the time of travel from the sun to the earth is not long enough to make the matter rotate with the same angular velocity as the sun. This is in reality a consequence of the fact that the velocity of emission is higher than the magneto-hydrodynamic velocity. The result is that the angular momentum is conserved so that the beam gets the same geometrical shape as in Chapman–Ferraro's theory.

On the other hand, outside the beams the flow is directed inwards and much slower. There may be time enough to establish a state of rotation with the same angular velocity as the sun. Sandström [8] has found that after application of Brunberg–Dattner's correction the tangential component of the diurnal variation is remarkably constant. This very interesting result seems to indicate that isorotation is established in interplanetary space at the solar distance of the earth's orbit.

It is possible that the magnetic field transfers momentum from the sun to its environment. This will cause a drag so that a tangential component is introduced.

4. FORBUSH STORM EFFECT AND THE 27-DAY RECURRENCY

It is of special interest to see how the Forbush storm effect and the 27-day recurrency is accounted for by the model. The influence of a beam on cosmic rays moving in the equatorial plane has been treated by Brunberg and Dattner [9]. Recently Block has started detailed calculations of the orbits of cosmic rays in the model field. A detailed theory cannot be worked out before these calculations are ready. However, already now it is clear that the effect is rather complicated and at least three different phenomena are of importance. This could be seen from a discussion of the motion in the equatorial plane of particles with so low energy that the radius of curvature of their paths is small compared to the distance sun–earth.

Fig. 4 shows the orbit of such a particle. When it passes a beam, (which contrary to Swann's opinion it could do even if the radius of curvature is small compared to the thickness of the beam) it will be influenced in the following way:

1. *Electric field effect.* The particle is decelerated by the electric field. This will cause a continuous decrease dI/dt in the intensity of cosmic radiation as long as the earth is inside the beam.

2. *Magnetic field effect.* Due to the difference in magnetic field inside and outside the beam the particle will drift outwards (from the sun) or inwards when it enters the beam. If outside the beam the intensity of cosmic radiation is a function of the solar distance, the intensity inside the beam will be different from outside the beam. It may be either higher or lower.

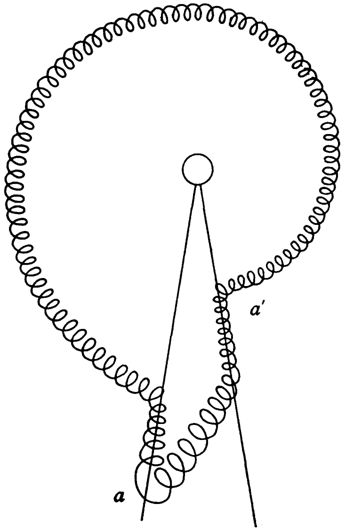

Fig. 4. Path of a high-energy particle in the accelerator model with crossed electric and magnetic fields (*Tellus*, **6**, 232, 1954).

3. *Capture effect.* Cosmic ray particles may be captured inside the beam which also means that certain orbits cannot be entered by particles from outside. When the beam moves outwards the captured particles are decelerated in the decreasing magnetic field in the beam. The present model does not give capture in the equatorial plane but probably in three-dimensional orbits. Further, a small disturbance in the magnetic field of the beam is enough to produce a capture of orbits in the equatorial plane.

If these three effects are superimposed the result may be shown in Fig. 5. If the K_p index is considered to be a measure of the electric field of a beam, we get a correlation between cosmic ray intensity and K_p index, which agrees with Kane's results [10]. However, it is in conflict with an

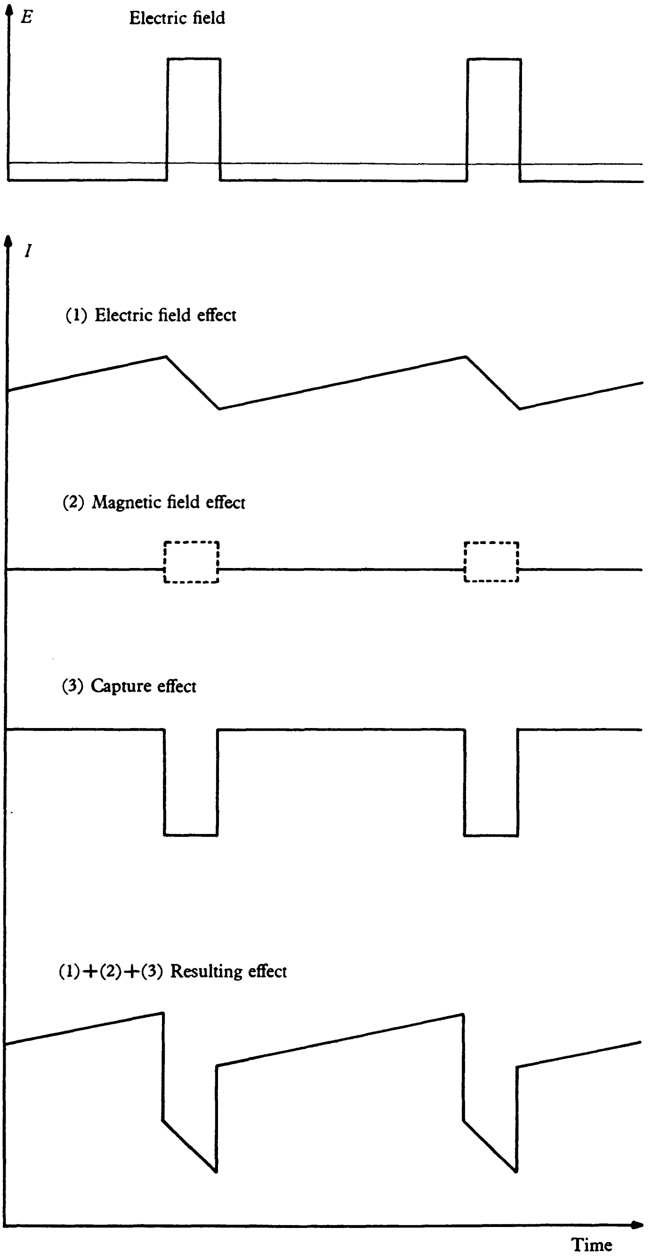

Fig. 5. When the sun rotates, the earth will be situated alternatively in a positive electric field (inside the beam) or in a small negative field (outside the beam). The cosmic rays will be affected in three different ways (1, 2 and 3 in the figure) which together give the resulting effect.

investigation by van Heerden and Thambyahpillai [11]. Venkatesan [12] will report about a similar investigation which supports Kane's results and gives an indication of the existence of at least effects (1) and (3).

5. POSSIBLE TURBULENCE IN THE MAGNETIC FIELD

Our model is designed in order to give a first approximation of the magnetic field in interplanetary space, but it is quite natural that the field should be superimposed by turbulent fields. It is an open question how important the turbulence is. I do not know any observed effect which calls for the assumption of turbulence in interplanetary space and in my opinion its importance has often been exaggerated. Interplanetary space may be considered as an extrapolation of the corona. Coronal photographs show a fine structure in the corona which may very well go far out in interplanetary space, but there is no indication of a large-scale turbulence. Although a small-scale turbulence, associated with the granulation, may exist, it seems more difficult to assume a turbulence with large elements. Especially, I cannot see any reason to introduce an extremely turbulent beam or cloud as Morrison [13] and others do. It is much easier to capture cosmic rays and to produce forbidden orbits in a rather regular field like the field of our model than in violently turbulent fields.

REFERENCES

[1] Alfvén, H. *Tellus*, **7**, 50, 1955.
[2] Alfvén, H. *Tellus*, **6**, 232, 1954.
[3] Alfvén, H. *Tellus*, **8**, 1, 1956.
[4] Gold, T. This symposium, Paper 30.
[5] Alfvén, H. *Nature, Lond.* **168**, 1036, 1951; *Ark. Fys.* **4**, 407, 1952; *Tellus*, **8**, 1, 1956.
[6] Alfvén, H. and Lehnert, B. *Nature, Lond.* **178**, 1339, 1956.
[7] Lehnert, B. Comment given on p. 245.
[8] Sandström, A. E. *Tellus*, **8**, 18, 1956.
[9] Brunberg, E. Å. and Dattner, A. *Tellus*, **6**, 254, 1954.
[10] Kane, R. P. *Phys. Rev.* **98**, 130, 1955.
[11] Heerden, I. J. van and Thambyahpillai, T. *Phil. Mag.* [7], **46**, 1238, 1955.
[12] Venkatesan, D. This symposium, Paper 37.
[13] Morrison, P. *Phys. Rev.* **101**, 1397, 1956.

Discussion

Parker: I would like to know how the close approach to isotropy (within ± 0·5 %) following the onset of a Forbush decrease of 10 % (presumably produced by a beam) can be reconciled with a large cosmic ray decrease of 10 %. The 10 % effect of a beam is essentially entirely anisotropic.

Alfvén: In absence of the electric field the cosmic radiation would become isotropic very quickly because of scattering, so it is only the electric field, or we can say the 'wind', which produces the anisotropy. The anisotropy during the storm becomes larger. In a paper presented at the Guanajuato conference Sandström has made a division of the cosmic ray variation into one tangential and one radial component. What comes out is that the latter is independent of the K_p but the former is a function of the K_p. The variation in the anisotropy is in good agreement with the model I have presented. What happens during the storm is, to the first approximation, that the voltage of the earth is changed when it passes across an electric field and that changes the whole cosmic ray intensity. When the voltage is changed the intensity is changed but not the anisotropy.

Singer: I want to make two remarks to Alfvén and to some extent also to van de Hulst (paper No. 1). One has to do with the winds in interplanetary space, I think this is a nice way to put it. I do not know any method of detecting these winds but I will report briefly that one can calculate the equilibrium charges of dust particles in interplanetary space and this charge comes out to be very highly positive. It is controlled merely by the solar photo-electric effect and also by the electron density and the electron temperature in the region of the dust particles. One of the interesting consequences of this is that the winds, such as are produced by corpuscular streams, will tend to carry these dust particles far up, away from the sun. There might be a way of observing the 'sweeping out', for example by studying the outer corona of the sun before and after solar activity.

Alfvén: The interplanetary dust is surely important here. It is of interest to see to what extent it moves with the beam and of course it will be best studied from a satellite.

Singer: The other remark has to do with the emission of the beam. The omitted beam will be a supersonic jet and the density is high, 200–800/cm^3. Then, turbulence will be set up. This could perhaps explain the absence of low-energy cosmic ray particles and why they reappear during low solar activity. Lumps with large magnetic field and high density created in this way will act as very effective sinks for low-energy particles (see paper to appear in *Phys. Rev.*). This cosmic ray effect would, in addition, provide a method of observing the onset and decay of the turbulence.

Alfvén: A crucial thing here is the importance of the shock-waves. The model here is a stationary one. It should only be taken as a first approximation and there are some obvious difficulties with this model which you see immediately.

It is natural that there should be turbulence in interplanetary space. But the importance of this is difficult to estimate. From the structure of the solar corona and from the rather long regular pattern which Gold has shown us, you do not get the impression that the large-scale turbulence is very important. In my model of the magnetic field it is neglected, but it is quite reasonable that we should introduce some turbulence at a later point. On the other hand, it is quite likely that the field has a fine structure. The structure of the corona may very well penetrate outwards. However, at present I can see no meaning in introducing a turbulent field and, as far as I know, there is no phenomenon which calls for the introduction of turbulence, so I think we could forget it at present. The extremely turbulent clouds which Morrison has proposed do not produce any effect which could not be produced much easier with the present model. For example, in the beam you could get captured orbits which give the same decrease as is obtained with these turbulent clouds, but with the beam you get them with much lower magnetic fields and in a much easier way.

Gold: The cosmic ray flare effect does not allow us to suppose that a very particular position on the sun is required to let the particles come to the earth, as the very greatest flares are known to be responsible; if an improbable condition of position has to be satisfied then it would be unlikely that the few largest flares would have satisfied this.

Further, the very great extension, as far as the earth, of coronal streamers is also made a difficult concept because of the solar rotation. Some of these streamers are long lived, and it would be necessary to suppose the gas at the earth to go around once in 27 days. At some distance this situation must clearly break down.

Alfvén: I think that this model works out to some earth radii. It is likely that matter at the earth's orbit takes part in the rotation, but this requires a much lower density in the interplanetary space than what is usually assumed.