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The Sun's General Magnetic Field

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Abstract

The solar magnetic field, including the interplanetary field is discussed. It is pointed out that in the absence of a theory of the Zeeman-effect in a turbulent atmosphere it is at present impossible to derive a value of the sun's general magnetic field from spectroscopic measurements.

From the magneto-hydrodynamic theory of sunspots a value of the sun's general magnetic field can be derived. Ananthakrisnan's diagrams of the prominence activity can be interpreted as due to the same disturbance wave as is causing the sunspots. This gives further confirmation to the theory, which indicates magnetic field of $H_p = 12$ gauss.

The magnetic field outside the sun (interplanetary field) is certainly far from a dipole field. An approximate model of the field is tentatively suggested. This model is in agreement with information derived from cosmic ray and magnetic storm data and is also reconcilable with the coronal ray structure.

1. Introduction

At present the discussion about the general magnetic field of the sun is very confused. This seems to be due to the almost general acceptance of two altogether unfounded assumptions about the field:

1. It is usually assumed that outside the solar surface the field is necessarily a dipole field. This would be true if in this region there were no electric current. The conspicuous violent disturbances in the corona, the occurrence of magnetic storms and aurorae, and the variations in the cosmic radiation are clear indications of changes in the electromagnetic state of interplanetary space which must be associated with electric currents and drastic deviations from a dipole field.

2. Also quite without any justification it is assumed that Zeeman-effect measurements give an accurate value of the solar magnetic field. The experimental technique has advanced in an admirable way from the time when Hale's measurements indicated the existence of a general field of + 50 gauss to the present days when BABCOCK (1955 a, b) claims a value of — 0.5 gauss. There is probably no objection to the present *measurements* of the Zeeman-effect displacement, but still *there does not exist any theory of the Zeeman effect in a turbulent atmosphere*. The granulation shows that the photosphere is in a turbulent state and this must affect also the magnetic field, so that it becomes turbulent. This means that the temperature T, the density ϱ and the magnetic field H are coupled and it is not at all likely that the average Zeeman effect gives an average of the magnetic field.

The turbulence converts kinetic energy into magnetic energy and back again. Under the assumption of equipartition the turbulent magnetic field was estimated to a few hundred gauss (H = 160 gauss – 500 gauss) (ALFVÉN, 1950, p. 146). BATCHELOR (1950) has raised some doubts about the equipartition for large turbulence elements, but this objection seems not to be applicable to the granulation. Compare also CHANDRASEKHAR (1950, 1951) and KULSRUD (1955). COWLING (1953) has discussed the problem from different points of view and his results essentially confirms the existence of at least an approximate equipartition.

Thus there are good reasons to suppose that in the photosphere there is a turbulent magnetic field of the order of, say $H = 300$ gauss. This cannot be detected by the present methods because of the lack of resolution. Babcock's measurements refer to surface elements which contain many thousand granulae. Suppose that in a small surface element $d\sigma$ of the photosphere the magnetic field component in the direction of the line of sight is H_z. It seems to be generally supposed that the measured field is the simple average

$$\bar{H}_z = \int H_z d\sigma / \int d\sigma \qquad (1)$$

This would be true in a uniform atmosphere without turbulence, but in the actual case we must introduce a *weight function* $f(\varrho, T)$ because the absorption of a spectral line is a function of the density and the temperature. Hence what is measured is

$$\bar{H}'_z = \int H_z f(\varrho, T)\, d\sigma / \int f(\varrho, T)\, d\sigma \qquad (1')$$

Let us assume that there is a general field H_0 of the order $H_0 = 10$ gauss. This is superimposed by the turbulent field H_t, so that in some parts of a granula the resulting field is $H_0 + H_t = +10 + 200 = +310$ gauss, whereas in other parts of it the field is $H_0 - H_t = +10 - 300 = -290$ gauss. The average from (1′) depends on the function $f(\varrho, T)$ and the way in which ϱ and T are coupled with H. If f is systematically smaller for positive values of H_t than for negative values, $\bar{H}'$ may very well be negative even if the real field $\bar{H}$ is positive, and its absolute value may differ by orders of magnitude).[1] Hence no conclusion can be drawn about the general magnetic field from the Zeeman-effect measurements and the results of these measurements are not relevant for our problem.

[1] An example of this was discussed recently (ALFVÉN 1952). It was shown that with a certain (rather specialized) coupling between H, ϱ, and T a reversal of the field takes place. It is obvious that the reversal can be produced also under more general conditions.

2. Field inside the sun

The solar magnetic field is obviously generated by some current system in the sun's interior, probably in the solar core. It is very likely that the currents are produced by some magneto-hydrodynamic mechanism, but although much work has been done in the field by COWLING (1934, 1945), ELSASSER (1946, 1947, 1950, 1954), BULLARD (1948, 1949, 1954), PARKER (1954 a, b), FERRARO (1937), BIERMANN (1950), TAKEUCHI and SHIMAZU (1952) we are still far from a complete understanding of the origin of the sun's—as well as the earth's—general magnetic field.

We can get information about the solar field by studying the way in which magneto-hydrodynamic disturbances are propagated.

According to the magneto-hydrodynamic theory of sunspots (ALFVÉN, 1950, p. 116) magneto-hydrodynamic waves are generated in the central parts of the sun and travel outwards along the magnetic lines of force. When they reach the solar surface they produce sunspots. The theory has been worked out under the assumption that inside the sun the magnetic field can be approximated as a dipole field in a spherical shell between a central distance R_1 and the solar surface R_0 and as a homogeneous magnetic field inside R_1. Recent results (ALFVÉN, 1953) indicate that the field inside the sun also has a tangential component, but as the m.-h. velocity is proportional to the magnetic field, this component affects only the longitudinal displacement, and in the present paper only latitude displacements will be discussed. LEHNERT (1954, 1955) has shown that the Coriolis force modifies the m.-h. velocity but for the relatively high frequencies associated with sunspot whirl rings the change is not very large.

When a wave produced by a disturbance in the central parts of the sun proceeds outwards, it reaches the solar surface at first at high latitudes and proceeds towards the equator. In this way the progression of the sunspot zones from high latitudes towards the equator is explained.

If at a certain time the wave front coincides with the equatorial plane near the centre of the sun, the time $T(\alpha)$ when it reaches the latitude α of the solar surface is given by

$$T(\alpha) = AF(\alpha) + BG(\alpha) + \text{const.}$$

where the first term derives from the motion in the dipole field and the second term from the homogeneous field (ALFVÉN, 1945). A and B are constants, $F(\alpha)$ is a function which is tabulated in the cited paper (ALFVÉN, 1945, p. 11) and $G(\alpha)$ can be approximated as

$$G(\alpha) = \sin^2 \alpha$$

If $B = 0$, corresponding to $R_1 = 0$ (only dipole field), T has its smallest values for $\alpha = 90°$ so that the wave front reaches the surface at first at the pole and from there proceeds to the equator. However, if B is sufficiently large, corresponding to a sufficiently large value of R_1, T may have a minimum value at a latitude α_{min} somewhere between the pole and the equator. This means that the wave front reaches the solar surface at first at latitude α_{min} from where it proceeds both towards the equator and towards the pole.

In the cited paper (ALFVÉN, 1945[1]) it was found that the observational sunspot progression curve was intermediate between two theoretical curves with

$$A = 1.22 \cdot 10^{-33};\ B = 108 \cdot 10^7;\ R_0 = 7.0$$

and

$$A = 0.41 \cdot 10^{-33};\ B = 25 \cdot 10^7;\ R_0 = 6.5$$

and perhaps more similar to the first one than to the second one. The two curves are shown in

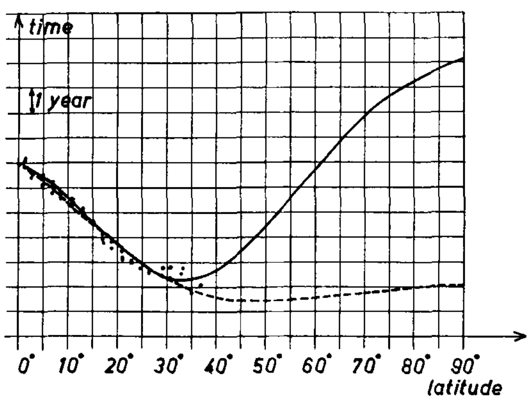

Fig. 1. Theoretical curve for the progression of the m.-h. wave front. (From Cosm. El. p. 123.)

——— $A = 1.22 \cdot 10^{-33};\ B = 108 \cdot 10^7;\ R_0 = 7.0 \cdot 10^{10}$
- - - - $A = 0.41 \cdot 10^{-33};\ B = 25 \cdot 10^7;\ R_0 = 6.5 \cdot 10^{10}$

[1] At the bottom of p. 15 in this paper there is a numerical error. The value of $F(0)$ should be $22.8 \cdot 10^{40}$ instead of $28.4 \cdot 10^{40}$. This changes the values of A, B, a and R_1. The corrected values are used in the present paper.

Fig. 1 together with the sunspot data. The first one has a maximum at about $\alpha = 33°$, the second one at about $\alpha = 50°$. The figure is the same as in the cited paper (with the difference that a small numerical error has been corrected and the high-latitude part has been included).

In the earlier paper the high-latitude parts of the theoretical curves were not drawn because they were not supposed to be of any importance as no sunspots are observed above 30° to 40°. It is of interest to note, however, that high latitude solar activity shows a tendency to move polewards periodically. The poleward motion of *solar prominences* is well-known since long through the works by ABETTI (1938), d'AZAMBUJA (1941) and others. Recently a diagram published by ANANTHAKRISNAN (1952) shows very clearly that the prominence activity at high latitudes moves towards the pole in a way which is similar to the progression of the high-latitude branch of the m.-h. wave front according to Fig. 1.

Hence there is a possibility that *not only the sunspots but also the high-latitude prominence activity is caused by the same train of m.-h. wave.* When the waves reach the solar surface they produce electromagnetic disturbances, which for some reason manifest themselves as sunspots at low latitudes but as prominence activity at high latitudes. We are going to discuss this possibility.

Hence we want to investigate whether both the observational sunspot progression curve and the maximum prominence activity in Ananthakrisnan's diagram could be represented by the same theoretical curve and then to calculate the parameters A and B of this curve. The observational sunspot progression curves[1] have been calculated for the cycles 11—16 and Ananthakrisnan's diagram covers the cycles 14—18. Hence the cycles 14, 15 and 16 are suited for our analysis.

From the sunspot progression curves we take the time T_{30} when the curves pass the latitude $\alpha = 30°$ and the time T_0 when it passes the equator. On Ananthakrisnan's diagrams the best defined part is the time of arrival T_{90} of the activity wave to the pole. There are also some fairly well defined maxima at 55°,

[1] See Cosmical Electrodynamics p. 120—122. Fig. 5.6 and 5.7.

Table 1

Cycle	T_0		T_{30}		T_{55}		T_{90}		$\triangle_0^{55}$		$\triangle_0^{90}$	
	N	S	N	S	N	S	N	S	N	S	N	S
14	08.7	09.3	04.1	4.7			06.1	07.2			2.6	2.1
15	20.3	20.7	15.7	16.1	14.9	15.0	17.6	18.0	5.4	5.7	2.7	2.7
16	31.2	31.0	26.6	26.4	23.5	24.1	26.7	27.0	7.7	6.9	4.5	4.0

Mean 3.1 years

but these are sometimes double. We design the time of these maxima by T_{55}. Table 1 gives the values of T_0 and T_{30} from the diagrams in Cosmical Electrodynamics p. 120—121 and T_{55} and T_{90} from Ananthakrisnan's paper. The table also gives the differences

$$\triangle_0^{55} = T_0 - T_{55}$$
$$\triangle_0^{90} = T_0 - T_{90}$$

The difference $\triangle_0^{30} = T_0 - T_{30}$ is always $\triangle_0^{30} = 4.6$ years because the observational points are fitted to the average observational curve (fig. 5.7 in Cosmical Electrodynamics). The maximum T_{55} for cycle 14 is not included in Ananthakrisnan's diagram.

The mean of $\triangle_0^{90}$ is

$$\triangle_0^{90} = 3.1 \text{ years.}$$

We can now determine the parameters A and B from the equations

$$\triangle_0^{30} = T(0) - T(30) = A\,[F(0) - F(30)] + $$
$$+ B\,[\sin^2 0° - \sin^3 30°]$$
$$\triangle_0^{30} = T(0) - T(90) = A\,[F(0) - F(90)] +$$
$$+ B\,[\sin^2 0° - \sin^2 90°]$$

or

$$\triangle_0^{30} = A\,[F(0) - F(30)] - 0.25\,B$$
$$\triangle_0^{90} = A\,[F(0) - F(90)] - B$$

In the earlier paper two alternative hypotheses were worked out: either are the sunspots produced when the m.-h. waves reach the solar surface $R_0 = 7.0 \cdot 10^{10}$ or when they reach the surface $R_0 = 6.5 \cdot 10^{10}$. In the first case we have ${}^{7.0}F(0) = 12.2 \cdot 10^{40}$; ${}^{7.0}F(30) = -22.0 \cdot 10^{40}$; ${}^{7.0}F(90) = -65.8 \cdot 10^{40}$ which gives $A = 0.83 \cdot 10^{-33}$; $B = 55 \cdot 10^7$; $a = 2.2 \cdot 10^{33}$ gauss $\cdot$ cm^3: $H_p = 12$ gauss where a is the dipole moment and H_p the field at the pole.

In the second case we have ${}^{6.5}F(0) = 22.2 \cdot 10^{40}$; ${}^{6.5}F(30) = 28.6 \cdot 10^{40}$; ${}^{6.5}F(90) = 77.0 \cdot 10^{40}$, which gives $A = 0.46 \cdot 10^{-33}$; $B = 37 \cdot 10^7$; $a = 3.8 \cdot 10^{33}$ gauss $\cdot$ cm^3; $H_p = 22$ gauss.

The curves corresponding to these two alternatives are shown in Fig. 2. They are not very different and both agree with the observational sunspot progression curve within an error of a few months.

The reason why the curve for $R_0 = 6.5 \cdot 10^{10}$ was introduced into the sunspot theory was that it is possible that the m.-h. waves need only reach a certain distance below the solar surface in order to produce a sunspot, which may have its "roots" at a certain depth. It is more likely that prominences which are observed above the photosphere should be caused when the disturbance reaches or passes the photosphere itself. Hence it is reasonable to choose the curve for $R_0 = 7.0 \cdot 10^{10}$.

Fig. 3 consists of Ananthakrisnan's diagram into which the observational dots of the sunspot progression curves are introduced. They are taken from fig. 5.6 in Cosmical Electrodynamics. The theoretical curve $R_0 = 7.0 \cdot 10^{10}$; $A = 0.83 \cdot 10^{-33}$; $B = 55 \cdot 10^7$, is drawn through

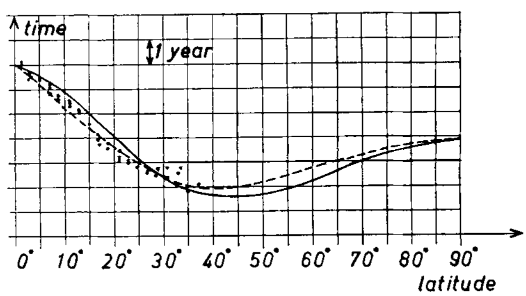

Fig. 2. Theoretical curves for the progression of the m.-h. waves

——— $A = 0.83 \cdot 10^{-33}$; $B = 55 \cdot 10^7$; $R_0 = 7.0 \cdot 10^{10}$
- - - - $A = 0.46 \cdot 10^{-33}$; $B = 37 \cdot 10^7$; $R_0 = 6.5 \cdot 10^{10}$

Dots are taken from Cosm. El. Fig. 5,7.

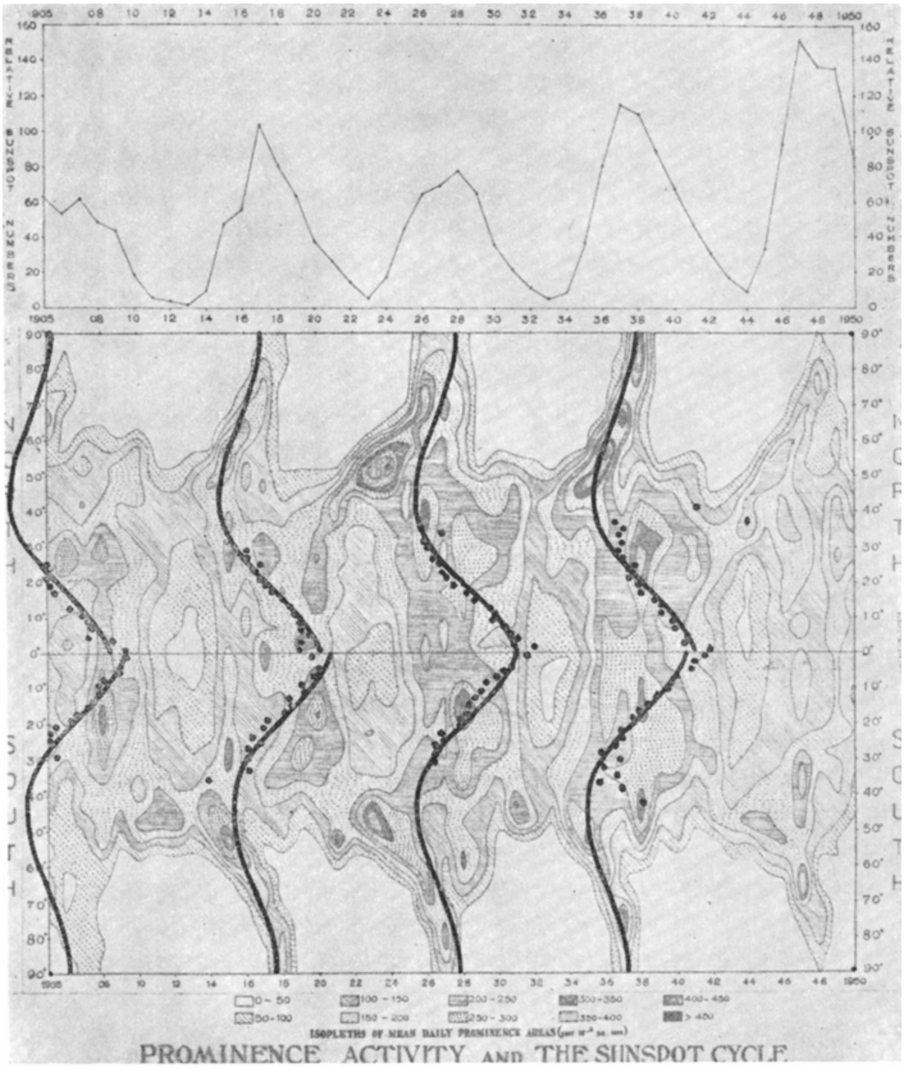

Fig. 3. Ananthakrisnan's diagram of solar prominences. The sunspot data from Cosm. El. Fig. 5, 6 are introduced. The curves are the full curve of Fig. 2, fitted to the sunspot dots.

these dots. It is seen that at high latitudes it represents the maximum prominence activity rather well, especially for the cycle 15. For the earlier part of cycle 14 the prominence data are lacking. In cycle 16 the maximum activity at 50°—55° comes about one year too early.

Since this analysis was made, the sunspot data for cycle 17 have become available. The sunspot progression curve has been constructed in the same way as earlier and plotted in the diagram. It is evident from Fig. 3 that the curve represents the prominence activity in a satisfactory way.

In the cited paper (ALFVÉN, 1945) the solar magnetic field was determined to be between the limits

$$37 \text{ gauss} > H_p > 9 \text{ gauss}.$$

The value which corresponds to the curves in Fig. 3 is

$$H_p = 12 \text{ gauss}.$$

3. Interplanetary field

In the absence of currents outside the sun, the field would be a dipole field. However, this field will be violently disturbed by the ejection of ionized gases from the sun. From solar observations we know that often there is an ejection of matter from prominences. Schuster, Chapman, and others have given good reasons for supposing that magnetic storms are produced by beams of ionized gas, which are ejected from the sun with velocities of the order of 10^8 cm/sec. and which go out to the earth's orbit and beyond it. Such beams cannot pass through a magnetic field without disturbing it violently, and if the solar field at a certain moment were a dipole field the first beam shot out from the sun would change its character drastically. In the region where the beam passes, the lines of force will be transported outwards with the beam. At some distance from the sun the field may derive to a larger extent from currents in space than from currents inside the sun. Hence the term "*the interplanetary magnetic field*" seems to be more appropriate than "the solar field".

The outward transport of field lines cannot go on indefinitely without a corresponding inward transport. This can be assumed to take place in the sections of the sun's field where for the moment no beam is ejected. In average over a long time the inward transport of magnetic flux must equal the outward transport.

The ejection of beams takes place in the sunspot zones on both sides of the equator. It is essentially limited to a belt between $+30°$ and $-30°$ latitude. Near the poles the solar field is much less disturbed and is probably not very far from a dipole field.

It is obviously difficult to construct a model of a field which is so complicated and so rapidly changing as the interplanetary field. Still it is very important to have a picture which gives some of the essential properties. The model, which we are going to propose, represents an ideal average field, a stationary state which always is considerably disturbed and probably has some sort of turbulence superimposed on itself. The model is a kinematic one. The problem of the dynamics of interplanetary space is very complicated and cannot be analysed in a satisfactory way at present.

In order to make the model as simple as possible we assume that the field is always meridional, i.e. the tangential component $H_t = 0$.

Further we assume that the field consists of four different parts limited by latitude angles φ_0 and φ_1 and longitude angles λ_b and $\lambda_b + \triangle\lambda$, the numerical values of which are discussed later.

1. *In the polar regions* $\varphi > \varphi_0$ and $\varphi < -\varphi_0$ the field is not very much disturbed. We approximate it to a *dipole field*. Hence if the dipole moment is a, we have

$$H_R = H_p \left(\frac{R_0}{R}\right)^3 \sin\varphi \qquad (1)$$

$$H_\varphi = H_e \left(\frac{R_0}{R}\right)^3 \cos\varphi \qquad (2)$$

with

$$\frac{1}{2} H_p = H_e = \frac{a}{R_0^3} \qquad (3)$$

The numerical values are

$$\frac{1}{2} H_p = H_e = 6 \text{ gauss}$$

$$a = 2.1 \cdot 10^{33} \text{ gaus cm}^3 \qquad (4)$$

The total flux is:

$$\Phi = \int_{\varphi_0}^{\pi/2} H_R \, 2\pi R \cos\varphi d\varphi = \pi R_0^2 H_p \cos^2\varphi_0 \qquad (5)$$

or

$$\Phi = 1.9 \cdot 10^{23} \cos^2\varphi_0 \text{ gauss} \cdot \text{cm}^2 \qquad (6)$$

2. *In the equatorial region* $+\varphi_1 > \varphi > -\varphi_1$ the field is disturbed by beams emitted from the sun. These beams occupy one or several sectors with longitudes $\lambda_b < \lambda < \lambda_b + \triangle\lambda$ where $\triangle\lambda$ is about 30°. Each part of a beam is supposed to move outwards radially with constant velocity. Because of the high conductivity the magnetic field components perpendicular to the velocity are "frozen in". As according to our assumption every volume element of the beam moves outwards radially at a constant velocity, a surface element in the equatorial plane expands as R^{-1}. This means that inside the beams the field is

$$H_\varphi^b = \frac{a_b}{R} \qquad (7)$$

where a_b is a constant which we shall determine later. Besides H_φ there is a radial field H_R which we shall discuss later. As the field is meridional the total flux should equal the flux

$$\Phi = \frac{1}{2} R_0^2 H_p \triangle \lambda \tag{8}$$

which passes the photosphere. Hence we obtain

$$\frac{1}{2} R_0^2 H_p \triangle \lambda = \int_{R_0}^{R_1} H_\varphi^b \triangle \lambda R dR \tag{9}$$

where R_1 is the outer limit to which the beam moves with its lines of force still going to the sun. As $R_1 \gg R_0$ we obtain approximately from (7), (8) and (9)

$$a_b = \frac{a}{R_0 \cdot R_1} \tag{10}$$

and

$$H_\varphi^b = \frac{a}{R_0 \cdot R_1} \cdot \frac{1}{R} \tag{11}$$

The numerical value of R_1 should be determined in such a way that the field in the neigbourhood of the earth's orbit gets a value which is in agreement with observations. From the theory of the storm effect of cosmic radiation we find values from $(H_\varphi^b)_\delta = 7\ \mu$ gauss to 70 μ gauss for small and for big storm effects. These values are acceptable in the theory of magnetic storms and aurorae (Alfvén, 1954; 1955). For our model we choose an intermediate value of

$$(H_\varphi^b)_\delta = 30\ \mu \text{ gauss} \tag{12}$$

This gives

$$R_1 = 6.5 \cdot 10^{13} \text{ cm}$$

and

$$H_\varphi^b = \frac{3 \cdot 10^{-5} \cdot 1.5 \cdot 10^{13}}{R} = \frac{4.5 \cdot 10^8}{R} =$$

$$= 6.5 \cdot 10^{-3} \frac{R_0}{R} \tag{13}$$

The value of R_1 is about 4 times the earth's orbital radius. This means that out to this limit the lines of force in the beam go back to the sun. The conditions outside R_1 shall not be discussed here.

3. In the equatorial region $+\varphi_1 > \varphi > -\varphi_1$, *outside* the beam there is a field which falls as

$$H_\varphi^a = \frac{a_a}{R^n} \tag{14}$$

where a_a is a constant. As in this region the field which once has been transported outwards by a beam is tending to go back to a dipole field, the exponent n should be somewhere between the dipole exponent 3 and the beam exponent 1:

$$1 < n < 3 \tag{15}$$

In reality the exponent n may vary with r, but in our model we assume it to be constant. Brunberg and Dattner (1954) have shown that the absence of an increase in cosmic radiation before a magnetic storm requires that near the earth the field is at least 10 μ gauss. They derive an average value of $n = 2.6$, but this is under the assumption that the value of a is higher than we have assumed. With our value n goes down somewhat, and we are still in a reasonable agreement with their results if for the case of simplicity we put

$$n = 2 \tag{15^1}$$

The same flux condition as above gives

$$\frac{1}{2} R_0^2 H_p (2\pi - \triangle \lambda) = \int_{R_0}^{R_1} H_\varphi^\alpha (2\pi - \triangle \lambda)\, R dR$$

where rather arbitrarily we have integrated between the same limits as for the beam. This gives

$$a_a = \frac{a}{R_0 \ln R_1/R_0}$$

and

$$H_\varphi^a = 0.88 \left(\frac{R_0}{R}\right)^2 \text{ gauss}$$

4. In order to satisfy the flux condition there must be regions $\varphi_0 > \varphi > \varphi_1$ and $-\varphi_0 < \varphi < -\varphi_1$ between the dipole regions and the equatorial region. In these regions the field is essentially radial. As flux from the interior dipole field is penetrating the solar surface, there must also be a radial field in the equatorial regions.

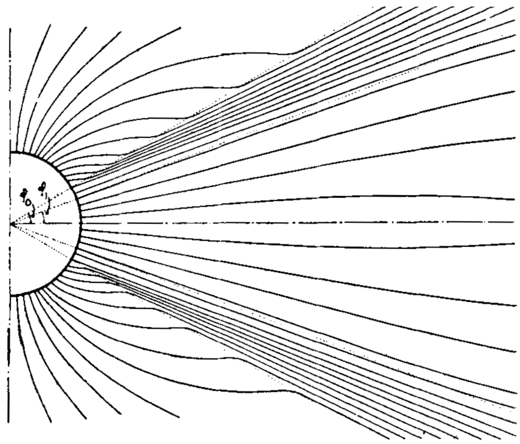

Fig. 4. The solar magnetic field inside a beam.

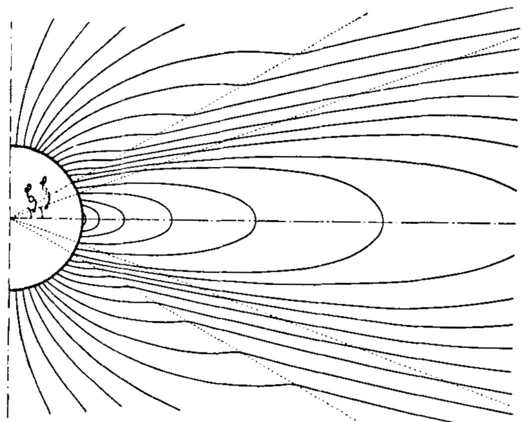

Fig. 5. The solar magnetic field outside a beam.

Fig. 4 and Fig. 5 illustrate the model. The limiting angles have been chosen as $\varphi_0 = 30°$; $\varphi_1 = 20°$. In the pictures the difference between the regions 2 and 4 is probably exaggerated. The beams go out with great velocity, and the flux they take with them has to be connected to the sun by the region 4. On the other hand, region 3 is characterized by the resetting of the field and the transition to 4 should be less pronounced.

In the equatorial regions (2 and 3) the model is the same as used in the theory of cosmic storm variation and local generation of cosmic radiation and in the theory of magnetic storms and aurorae (Alfvén, 1954; 1955). The model field in this region is shown in Fig. 6.

It should be observed that the continuity of flow requires a tangential streaming near the solar surface. The field outside the equatorial regions is of no importance in the theory of magnetic storms and aurorae. In the cosmic-ray theory the discussion was essentially confined to the conditions near the equatorial plane. The introduction of the present model makes it possible to extend the analysis also to regions far from the equatorial plane. This may call for modifications of some details in the cosmic-ray paper.

The beam is associated with an electric field

$$E_b = -\frac{v_b}{c} H_b$$

in the beam, so that there is a voltage difference V_b over the beam

$$V_b = R \triangle \lambda E_b = \frac{v_b}{c} \frac{\triangle \lambda a}{R_0 R_1} = \text{const.}$$

Outside the beam (in region 3) there is a field

$$E_a = -\frac{v_a}{c} H_a$$

associated with a voltage difference

$$V_a = (2\pi - \triangle\lambda) R E_a = \frac{v_a}{c} \cdot \frac{(2\pi - \triangle\lambda)\, a}{R_0 \ln (R_1/R_0)} \cdot \frac{1}{R}$$

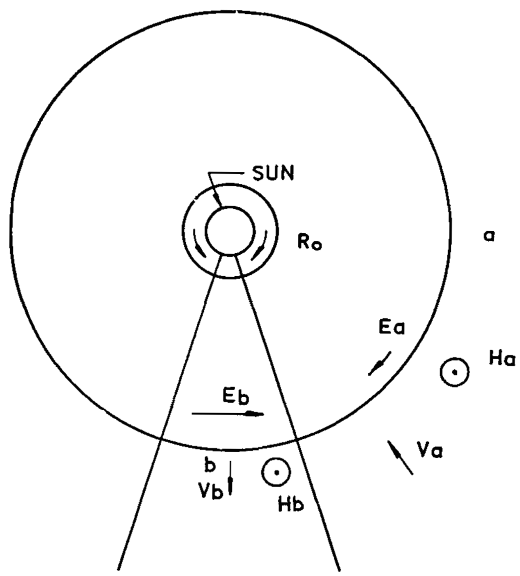

Fig. 6. Field model in the equatorial plane. (Tellus: Origin of Cosm. Radiation, **6**, p. 238).

Table 2

Region	Magnetic field H_φ				Radial field H_r	
		n	Sun's equator	Earth's orbit	Sun's surface	Earth's orbit
Polar Region	Dipole field	3	(6 gauss)	(0.6 μ gauss)	10 gauss	—
Equatorial region	Inside beam	1	0.065 gauss	30 μ gauss	2 gauss	50 μ gauss
	Outside beam	2	0.88 gauss	19 μ gauss	2 gauss	15 μ gauss

In our stationary model we have

$$V_a = V_b$$

$$v_a = v_b \frac{\triangle\lambda}{2\pi - \triangle\lambda} \cdot \frac{\ln (R_1/R_0)}{R_1} R$$

The compression of the gas in the region 3 may in part be compensated by a flow parallel to the lines of force.

The electric conditions in region 4 are more complicated. In fact they cannot be described in a satisfactory way in a stationary model, which shows one of the limitations of our model. In reality the conditions in region 4 are non-stationary and depend on the life time of the beam etc.

The driving mechanism of the ejection of beams is probably the intense heating of some parts of the solar atmosphere by solar flares and other kinds of solar activity. The heating makes the gas expand and this weakens the magnetic field. The very weak magnetic field in the beam near the solar surface is reconcilable with this process.

Table 2 gives the field in different parts of our model.

The values of H_r refer to a point near the limit of the transition region 4. In the equatorial plane we have $H_r = 0$.

The shape of the lines of force is given in the following way. A line of force which passes the solar surface at a latitude φ, intersects the equatorial plane at a point at the distance R. The flux Φ_1 between the equator and the latitude φ is

$$\Phi_1 = \Phi_0 \sin^2 \varphi$$

where

$$\Phi_0 = \pi R_0^2 H_p$$

is the total flux through the solar surface. Inside the beam the flux Φ_2^b between the equator and a circle in the equatorial plane with the radius R_1 is

$$\Phi_2^b = \Phi_0 \frac{R - R_0}{R_1 - R_0}$$

which gives for the two ends of the line of force

$$\frac{R}{R_0} = 1 + \left(\frac{R_1}{R_0} - 1\right) \sin^2 \varphi = 1 + 929 \sin^2 \varphi$$

The same relations for the region outside the beam are

$$\Phi_2^a = \Phi_0 \frac{\ln R/R_0}{\ln R_1/R_0}$$

and

$$\ln (R/R_0) = \ln \left(\frac{R_1}{R_0}\right) \sin^2 \varphi = 4.5 \sin^2 \varphi$$

The following table gives the intersections with the equatorial plane of the lines of force passing the solar surface at the latitude φ.

Table 3

Latitude φ	Distance in solar radii	
	inside the beam	outside the beam
0	1	1
5	8.1	1.05
10	29	1.23
15	63	1.58
20	110	2.23
25	167	3.38
30	233	5.50
35		9.3
40		17.0

4. Consequences of the solar model field

Near the equatorial plane the present model is essentially the same as used in the papers about the cosmic radiation and the magnetic storms and aurorae. This means that the model gives electric fields which are needed in order to explain the magnetic storms and aurorae, and it also explains the variation of cosmic radiation.

Further the model gives the progression of the sunspot zones towards the equator and the poleward motion of the prominences as a simple consequence of the motion of m.-h. waves in the sun.

The model seems to be in striking conflict with the Zeeman-effect measurements *if* these are interpreted in the naive way as really meaning an average field. It is possible that a magneto-hydrodynamic treatment of the turbulence in the photosphere will reveal that no real conflict exists.

The cut-off in the cosmic-ray spectrum has from time to time been quoted as an argument for or against a solar magnetic field. The present model is so far from a dipole field that the usual arguments are invalid. It may be that the cut-off is related to the solar magnetic field but in the way which has been discussed in one of the cited papers.

An argument which has been used against the assumption of a solar field is that solar flares often are accompanied by increases in cosmic radiation which follow within an hour after the flare (FORBUSH, STINCHCOMB and SCHEIN, 1950). This phenomenon has been studied, especially by Simpson's group (SIMPSON, FIROR and TREIMAN, 1954), with the neutron counter technique, which is sensitive in the rigidity region of some times 10^7 gauss · cm. If the solar field were an ideal dipole field, cosmic rays produced near the solar flare could not reach the earth, unless the dipole moment were very small (corresponding to a surface field of 10^{-4} gauss). The time lag is so small that particles generated near the sun cannot have time to diffuse along a very complicated orbit out to the earth.

The present model removes this difficulty because the magnetic lines of force run out radially from the equatorial region. Table 3 shows that in the beam there are lines reaching the neighbourhood of the earth ($R/R_0 = 200$) coming from $\varphi = 25°—30°$. Only relatively

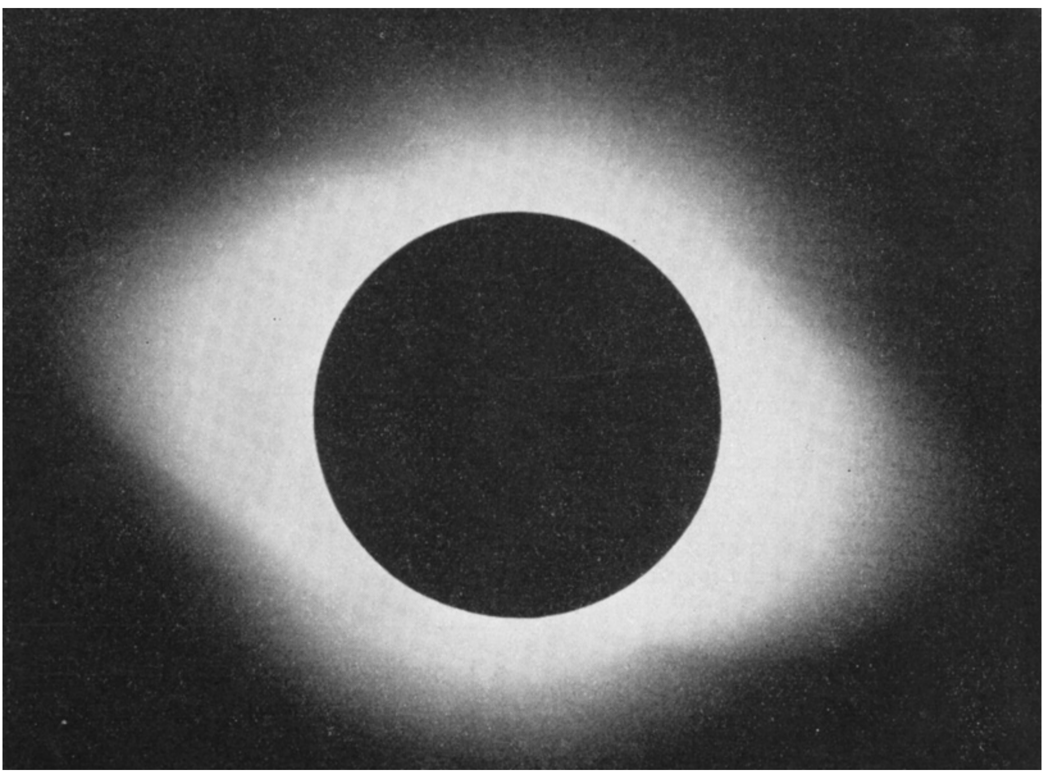

Fig. 7. Photograph of the solar corona. (Wallenquist 1954.)

small disturbances are needed in order to shift this point. Outside the beam the conditions are not so favourable, but even there a reasonable drift perpendicular to the lines of force, or a diffusion, will allow cosmic-ray particles to travel almost directly from the flare out to the earth. Usually they should reach the earth from the sun's direction, but due to the complicated structure of the magnetic field they may also come in from other directions. This explains that many of the flares produce increases in Firor's zones (FIROR, 1954) but that there also are many noteworthy exceptions, when flare effects have been observed far away from the expected zones.

5. Relation to the structure of the corona

If we compare Fig. 4 or especially Fig. 5 with a photograph of the corona during a sunspot minimum, we find some resemblance: The fine structure of the corona is similar to the magnetic lines of force of the model. The reasons for this may be the following.

The proposed model gives a simplified picture of the real conditions. There may be a superimposed turbulence, and especially near the sun's surface the model field is usually much disturbed by local fields from sunspots, etc. It is well known that the solar corona is very much influenced by sunspots and prominences (see e.g. van de Hulst). The corona should also be controlled to some extent by the general field. We whould expect that the general field is most important for the structure of the corona at times of sunspot minimum, when the influence of local solar activity is small, and at large distance from the centres of disturbance. Hence a comparison between the field model and the corona photographs should preferably be made for a sunspot minimum and refer especially to the outer corona.

This indicates that the similarity between Fig. 5 and a minimum corona may be significant. The "brushes" or rays near the poles are usually interpreted as given by the magnetic field, and this seems to be correct. The most prominent phenomena at lower latitudes are the "equatorial streamers" or "fans" which have a mainly radial fine structure. As long as it was firmly believed that the solar field was a dipole field it was impossible to identify this fine structure as given by the magnetic field lines. With the present model it seems plausible that *practically all the fine structure of the corona is given by the magnetic field.*[1] This may be true also during a sunspot maximum but then the magnetic field is influenced very much by local fields from sunspots and prominences. Our model of the magnetic field is perhaps too simple to account for the conditions near the sun at the time of a maximum. At large distances where the local disturbances are less pronounced it may be hoped that the model is a better approximation even during a maximum.

If we accept the identification of the fine structure of the corona as magnetic field lines, we will have a possibility to make a better model of the general magnetic field than the present model. The field is not necessarily symmetrical with respect to the equatorial plane; the beams may be shot out at any angles and are often much thinner.

[1] Note added in proof: At the conference in Guanajuato T. GOLD presented independent arguments for the same interpretation.

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