B. JOINT DISCUSSION
ON
SOLAR MAGNETIC FIELDS

Friday 18 August 1961 at 14^{h}00^{m}

ORGANIZING COMMITTEE: Dr Leo Goldberg, Dr H. Alfvén, Dr A. Severny, Dr M. Waldmeier
NEETING CHAIRMAN: Dr M. Minnaert
SECRETARIES: Dr Edith A. Müller and Dr K. O. Kiepenheuer

PROGRAM

1. The Solar Magnetic Cycle: *H. W. Babcock*
2. Magnetically Active Regions on the Sun: *A. B. Severny*
3. Sunspot Magnetic Fields and Loop Prominences: *V. Bumba* and *J. Kleczek*
4. Configuration of Magnetic Fields in Sunspot Umbrae: *V. Bumba*
5. The Sun's Magnetic Field from Radio Observations: *A. Hewish*
6. Variations of the Sun's Poloidal Magnetic Field: *M. Waldmeier*
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10. Un Magnétomètre Mesurant les Champs Magnétiques Perpendiculaires au Rayon Visuel. Applications a l'Etude des Champs Radiaux Autour des Taches: *A. Dollfus* et *J.-L. Leroy*
11. Magnetic Fields in Prominences at the Limb: *H. Zirin*

1. THE SOLAR MAGNETIC CYCLE
H. W. Babcock

First I should like to refer briefly to the observations that make this development possible. Records obtained with the improved solar magnetograph, showing the pattern of weak magnetic fields distributed over the Sun, and the changes in these fields, now enable us to specify many features of the topology of the lines of force, both above and below the surface. These observations depend on the Zeeman effect, which is fundamental and quantitative.

The magnetograph has been developed for automatically scanning the entire disk of the Sun with a resolution of 23″ in a period of one hour. Seven distinct electronically-calibrated levels of field intensity are recorded, along with the magnetic polarity of each point. The short recording line is made to slant to right or left to indicate magnetic polarity, while it is made to undergo abrupt changes in brightness or form at calibrated levels of 1 gauss, 2, 6, 10, 15, 25, and 60 gauss.

As was shown some years ago, optical activity occurs wherever the magnetic field is sufficiently strong. Generally, a BMR (bipolar magnetic region) emerges in a small and compact form. It grows rather rapidly until the magnetic field lines, looping through the surface, reach a maximum, after which the total flux seems to remain nearly constant. As the field intensity grows in a young BMR, calcium plages, faculae, and sunspots appear in that order. Later, the BMR expands, and gradually the various kinds of optical activity subside in reverse order as the field intensity weakens due to the expansion of the area. Finally, only the large, low-intensity field is identifiable, and gradually it merges into the background of other weak fields. The magnetic field is evidently fundamental to various kinds of solar activity.

I now wish to turn to a model showing the topology of the lines of force of the Sun's field and their variations. In addition to making use of some of the elementary ideas of magneto-hydrodynamics, it is essential to consider two of the primary observational findings. These distinctly limit the possible models. They are:

(1) Bipolar magnetic regions (BMRs) disappear by expanding, *not* by contracting and sub-submerging. This finding cannot be ignored.

(2) The Sun has a poloidal or main dipolar field, limited to high latitudes, which has been under observation since 1953. This dipolar field reversed its polarity near the peak of the current sunspot cycle. We assume that this is the usual course of events.

In brief outline, the model proposed here begins with a poloidal field whose lines of force lie in meridian planes. The submerged lines of force are shallow and are distorted by the differential rotation of the Sun, so that kinetic energy of rotation is converted to magnetic energy at an increasing rate as the lines of force are drawn out in longitude to form rather tight spirals—essentially toroidal fields—on opposite sides of the equator. This continues until the magnetic energy of the submerged toroidal fields attains locally a critical limit where instability sets in, forming concentrated flux loops that are brought to the surface by magnetic buoyancy. Each such loop produces a BMR on the surface, with related sunspots. Thus we see that the poloidal and toroidal components are simply parts of the same general magnetic field. By following the development of the lines of force, one finds that, as the BMRs expand and migrate, the initial poloidal field is neutralized and then supplanted by another of reversed polarity. Of perhaps fully as much interest, most of the magnetic flux that is created in the formation of the toroidal fields eventually finds its way through the photosphere and is liberated in the form of large, detached loops, high in the corona.

Consider as Stage 1 of our model the field as measured in 1953–56, which had a mean intensity of the order of one gauss. It was limited to latitudes above 55° and the total flux was estimated to be 8×10^{21} maxwells. In our model, the lines of force are taken to lie in a sheath of thickness 0·05 R below latitude 30°. At higher latitudes, the sheath thickens as it merges into the polar cap. The flux is sufficient to give a field, H_0, of 5 gauss in the sheath at the equator.

The differential rotation causes the lines of force in low latitudes to move ahead. Here the dashed lines represent surfaces of constant angular velocity, or 'isotachial surfaces.' The isotachs cut more deeply into the Sun than do the magnetic lines.

After the winding of the submerged lines of force has proceeded for about 3 years, the equator will have gained about 5·6 turns compared to the latitude circle at 55°. Because the angular velocity varies as $\sin^2 \phi$, the spiral winding is tighter in moderate latitudes than it is near the equator. Therefore, as the field grows, it will first become critically unstable at moderate latitudes. If we choose for the epoch of Stage 1 a time midway between sunspot maxima—that is midway between field reversals—this allows about 3 years of toroidal winding to occur before the onset of a new sunspot cycle.

Let us consider how the magnetic energy in a plasma is increased by drawing out the lines of force. Imagine a shallow cylinder with its axis in the meridian plane of the Sun. It contains a plasma with a magnetic field parallel to the axis of the cylinder. As a result of differential rotation, the cylinder will have become elongated, say to twice its original length. Because the plasma cannot cross the lines of force, the cross-section of the cylinder will be diminished to one-half, with doubling of the field intensity. Since the magnetic energy content varies as $H^2/8\pi$, the energy will be quadrupled by the elongation.

In the model, ψ is the angle of the toroidal lines with the meridian. We have seen that H_0, at the equator, is 5 gauss. At any latitude less than about $\phi = 30°$, the field in the sheath will be $H_0 \sec \phi \sec \psi$.

We wish to develop an expression showing how the critical latitude for the emergence of BMRs and sunspots decreases with the time, n, in years, since the onset of a sunspot cycle.

The angular velocity of the Sun as derived by Newton and Nunn from sunspots is

$$\omega = 14°\cdot 4 - 2°\cdot 8 \sin^2 \phi.$$

This is converted to differential advance in longitude as a function of n:

$$\theta - \theta_0 = 17°\cdot 6\,(n + 3) \sin^2 \phi$$

It is easy to write down an expression for $\tan \psi$, which we have defined:

$$\tan \psi = \mathrm{d}\theta/\mathrm{d}\phi = 35\cdot 2(n + 3) \sin \phi \cos \phi.$$

The expression for H as a function of latitude and ψ has already been derived. For $H_0 = 5$ gauss and $n = 0$, we have

$$H = 528 \sin \phi.$$

Therefore at $\phi = 30°$, where evidences of instability first occur, the field intensity in our (fictitious) sheath is about 260 gauss when sunspots begin to form. But at lower latitudes the field has not yet reached this intensity. As magnetic amplification continues, however, the critical value of the field intensity will be reached at progressively lower latitudes. After several spot groups have been formed at any given latitude, amplification at that latitude will be terminated by fragmentation of the submerged magnetic flux strands. It may be noted that amplification of the initial poloidal field by a factor of about 50 is attained by the time the critical value is reached for the emergence of flux loops at the surface, with the formation of BMRs and related sunspots.

By substitution we arrive at the following parametric equation which relates the interval n in years since the onset of a given sunspot cycle to the latitude, ϕ_c, at which the critical value of the magnetic field is being attained, with consequent formation of spots:

$$\sin \phi_c = \pm\, 1\cdot 5/(n + 3).$$

Note that for $n = 0$, the latitude is 30°, while for $n = 10$ the latitude is about 7°. This equation represents Spörer's law of sunspot latitudes. The graph of the equation (Figure 1) may be compared with the familiar 'butterfly diagram' of Maunder. The line of instability represented by the equation corresponds roughly to the 'leading edge' of the butterfly wing.

We may anticipate later developments by pointing out that the expanding lines of force above merging BMRs will largely be liberated in the corona, but some of them will neutralize and then replace the initial poloidal field of Stage 1 with another poloidal field of reversed polarity. Thus, 11 years after Stage 1, the situation will be the same except for reversed magnetic polarity of the poloidal field. A new cycle of amplification will then commence.

The concept of a uniform sheath that was assumed for calculation is too simple. Actually, owing to turbulence and to the effects of magnetic viscosity, the flux lines will develop irregular groupings and strands. Due to the greater forward velocity of the shallower layers, a twisting or vorticity will be induced in the strands and they will be rolled into so-called 'ropes'. These may be visualized as roller bearings. The field intensity in the ropes will be several times greater than in the uniform sheath, and it will be of the right order of magnitude for the formation of typical BMRs or sunspot groups, wherein the total flux is known to be roughly

10^{21} maxwells. Analysis shows that during each sunspot cycle of 11 years' duration, the total length of such flux rope produced by drawing out will be of the order of 10^3 solar radii. This is ample for the development of 1000 to 3000 BMRs, which is the number observed. The vorticity of the flux ropes will be propagated along their submerged sections to the BMRs where they break the surface. This can explain the characteristic pattern of the 'chromospheric whirls' first described by Hale.

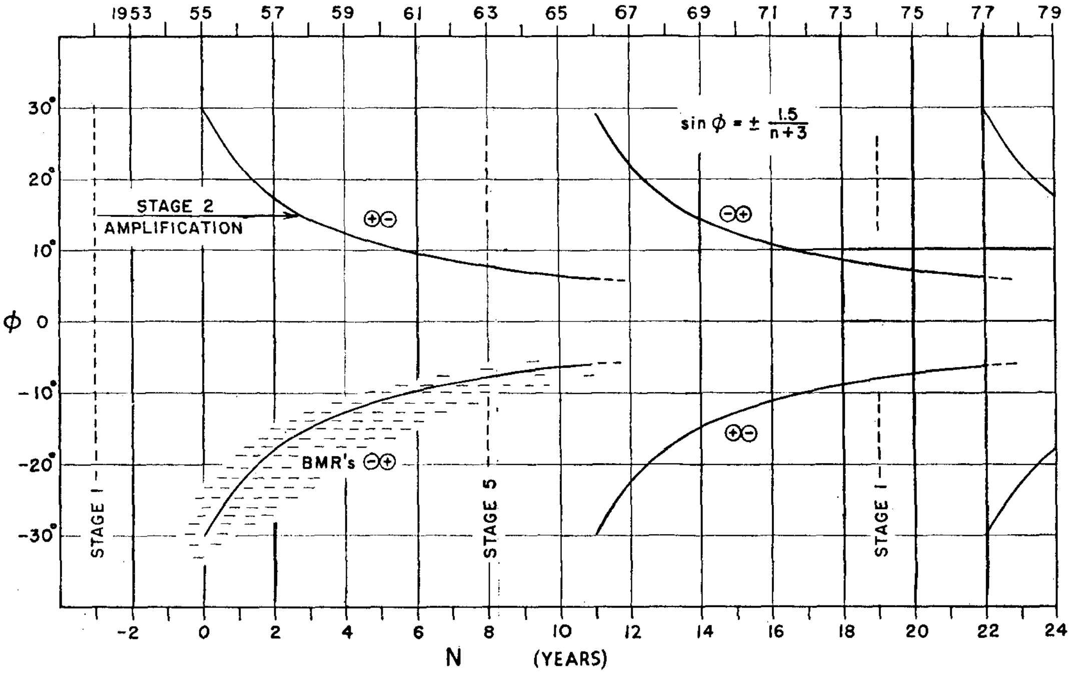

FIG. 1. The repetitive stages in the solar magnetic cycle are indicated as a function of time. In Stage 1 the lines of force lie in meridional planes. After amplification in Stage 2 the submerged fields become unstable and are brought to the surface. The curving lines in the graph represent the zones of appearance of BMRs according to the derived relationship between latitude and time; they may be compared with the Maunder 'butterfly diagram'. As the cycle declines, Stage 5 is reached, which is similar to Stage 1 but with reversed polarity.

This model properly accounts for Hale's laws of sunspot polarity and it is capable of giving a qualitative account of the predominance of preceding spots as well as of the recurrence of activity in limited zone of longitude.

As a BMR grows, there is a general expansion of the magnetic flux loops into the high atmosphere; this is consistent with the expansion of the observed magnetic areas on the Sun's surface and with the expansion reported for coronal features. This expansion is irreversible and is an essential part of the varying topology of the Sun's field.

We come now to the active stages of development of the model when many BMRs are forming and then disappearing by expansion. There is a slight tendency for the preceding parts of BMRs to expand toward the equator, while the following parts tend to expand or migrate poleward. Related to this is a drawing out in long, slanted configurations, seen in calcium plages as well as in the BMRs themselves. The polarity of the following part of a

BMR is opposite to the magnetic polarity of the polar cap toward which it expands. Figure 2, which is a meridian section, indicates schematically how a part of the initial dipolar field is neutralized by the expanding loops above a BMR. The stages of development are in the order *a*, *b*, *c*. Severing and reconnection must occur when the BMR interacts with the main field; thus, the parts labelled *b* are eliminated and a large loop of flux is detached in the corona.

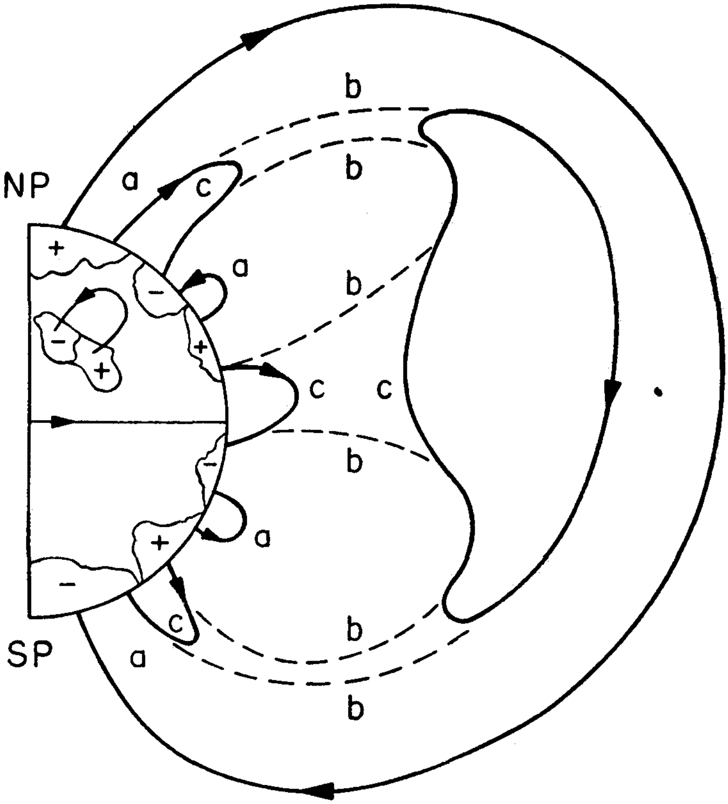

FIG. 2. Far-reaching external field lines of the poloidal field are shown, together with the meridional component of the coronal field loops above expanding BMRs. Severing and reconnection of the approaching field lines account for reversal of the poloidal field, with liberation of detached loops in the corona.

Also, loops are left both in high latitudes and over the equator. These link the photosphere to a shallow depth, and presumably are able to slip free owing to the enormous reduction in conductivity that occurs in the photospheric layers because of turbulence. The theoretical work of Sweet bears on this point.

There is about 100 times as much magnetic flux available from the numerous loops over BMRs as is required to neutralize and then supplant the initial poloidal field of Stage 1 with one of opposite polarity. This not only provides an ample factor of safety, but some further interesting consequences. Many of the flux loops above BMRs may become radially extended to great distances before they are detached as indicated below.

By far the greater part of the field lines are disposed of as indicated in Figure 3. This is a section parallel to the equator. Numerous BMRs formed in various longitudes around the Sun tend to merge into each other as they expand. Thus the preceding part of one BMR merges with the following part of the next BMR to the west, and so on around the Sun. As indicated in the diagram, the approaching flux loops as at *c—c*, which are anti-parallel, neutralize each other with reconnection as in part *d*. This occurs repeatedly, and results again in the liberation of detached field loops in the corona.

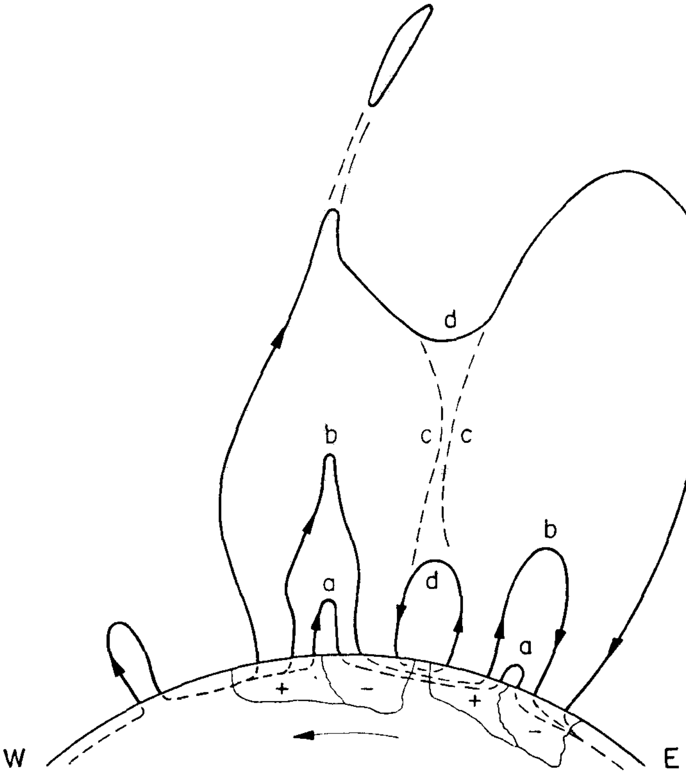

Fig. 3. The field loops above expanding BMRs may become extended radially to great distances, but eventual merging of BMRs to east and west, as shown in this section parallel to the Sun's equator, results in liberation of loops and belts of magnetic flux in the corona. The cumulative effect of the merging of hundreds of BMRs is the liberation of most of the field lines that were generated in Stage 2 as submerged toroidal fields by the action of the Sun's differential rotation.

Such detached field loops or 'magnetic bubbles' are capable of entrapping charged particles having a wide range of energy. Thus, the bubbles, moving outward into interplanetary space at relatively slow speed, may carry within themselves a collection of very energetic particles.

As the terminal stages of the sunspot cycle are approached, the residual activity at low latitudes will diminish. The toroidal fields formed earlier will largely have escaped into the corona. The situation will be similar to that of Stage 1, except that the poloidal field will have reversed polarity. Because the equatorial acceleration continues in the same sense, the analogues of the preceding stages will occur, thus constituting the second half of the 22-year magnetic cycle. This will be repeated indefinitely, as long as the driving energy is available.

Finally, let us consider the effect of the magnetic fields on the energy balance of the corona. A recent discussion by Osterbrock leads to the result that the loss of energy by the corona is about 1×10^5 ergs/cm^2 sec. Extended over one 11-year cycle, this amounts to 2×10^{36} ergs. Now we have just seen that about 99 per cent of the magnetic field lines generated when the submerged toroidal field is formed eventually pass through the photosphere into the corona. There the magnetic energy must be dissipated by Joule heating in either of two ways: when anti-parallel field lines merge and neutralize one another; or when detached loops and magnetic bubbles immersed in plasma drift outward. When the detached magnetic loops are carried sufficiently far from the Sun they must reach eventually a region where the density is so low that the lowered conductivity will permit their collapse, with consequent conversion of the magnetic energy to thermal energy of the medium. An estimate of the magnetic energy going into the toroidal fields during the amplification process is readily made, and turns out to be 10^{36} ergs in each sunspot cycle. Additional energy must be supplied by the expanding gas above BMRs when the flux loops are inflated during their expansion. Therefore it seems that Joule heating of the corona by conversion of magnetic energy may be of the correct order of magnitude to match the calculated heat losses. Much of this energy conversion would occur at rather high levels in the corona.

DISCUSSION

H. Zirin. As I understand it, your model derives the magnetic field energy from the solar differential rotation. Have you calculated the resulting rate of decay of the differential rotation?

H. W. Babcock. The model proposed here calls on the kinetic energy of the Sun's differential rotation to provide the magnetic energy going into the toroidal fields. If it were not replenished, this would be adequate for only a few thousand years, as Alfvén has shown. Therefore the problem of the maintenance of the differential rotation assumes a greater importance. The differential rotation is, however, an observed fact, and magnetic amplification is a direct consequence.

V. C. A. Ferraro. Does your theory predict the period of the solar cycle?

H. W. Babcock. Given the initial poloidal field and the observed differential rotation, the period follows provided that the critical value of the amplified toroidal field, necessary for formation of BMRs through instability, can be predicted. Here we have obtained the critical value empirically at latitude 30° and have used it to predict the rate of appearance of sunspots at lower latitudes.

T. Gold. I comment on the solar cosmic ray evidence of the cutting off of lines of force of magnetized clouds from the Sun. The connection might be maintained for several days but not for several weeks, because then the field on the solar surface would increase unduly. From the separation of two different geomagnetic storms a disconnection time of a few days can be inferred.

F. Hoyle. Calculations, about which I shall report at Cloudcroft, indicate that the disconnection time scale mentioned by Gold is of the order of several weeks. The precise value depends on the strength of the magnetic field, and on the dimensions of the disconnected region.

R. Lüst. With respect to the time scale of several weeks for the dissipation of the magnetic fields, as stated by Hoyle, it seems to me difficult to explain the heating of the solar corona in this way.