PART IV

SOLAR AND INTERPLANETARY MAGNETIC FIELDS

PAPER 26

PHOTOSPHERIC MAGNETIC FIELDS

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ABSTRACT

Since 1952 a total of 635 magnetograms of the sun have been obtained in a systematic investigation of weak magnetic fields in the photosphere. The frequent records give the location, polarity, and intensity of weak fields down to a fraction of 1 gauss, although with resolution limited to about 0·04 of the solar diameter.

Confirmation of previously reported results in 1954 comes from continuation of the series and from observations with a second, improved magnetograph on Mount Wilson. Three types of field pattern are found: (1) the poloidal field in high heliographic latitudes, consistently positive in the north, negative in the south, with intensity of the order of 1 gauss; (2) BM (bipolar magnetic) regions, often weak and extended, but which when strong are associated with plages, spots, flares, coronal emission, chromospheric fine structure, and filaments; and (3) UM (unipolar magnetic) regions, rather extended and weak, occurring in low latitudes, and associated in time with 27-day recurrent geomagnetic storms and cosmic-ray fluctuations. Attention is directed to the probable disposition of the magnetic flux in the high atmosphere and in interplanetary space, consistent with the observed magnetic areas and with the restriction div $\mathbf{H} = 0$.

Alfvén has argued that the interpretation of the small Zeeman displacements is meaningless and irrelevant because the rather strong turbulent fields presumed to prevail in granules might be coupled systematically, in respect to magnetic polarity, with the intensity of the absorption lines used for measurement. But this would produce a bias, with a shift of zero point of magnetic intensity, for all observed fields on the disk, and no such bias is observed. The measurements, while limited in resolution, are on an absolute scale, and show, for the 'quiet sun', vast areas with only small random fields no greater than a few tenths of 1 gauss.

The solar magnetograph is an instrument for the measurement and recording of weak magnetic fields in the photosphere of the sun (Babcock [1]). It combines a powerful grating spectrograph with an oscillating analyzer and a sensitive photo-electric detector for measurements of very small Zeeman effects in the spectrum. It responds to $H \cos \gamma$, the component of the magnetic field in the line of sight, and by means of a scanning system with conformal recording, it maps the location, intensity, and

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polarity of magnetic fields on the disk of the sun. Spurious responses have been eliminated, so that the instrument, limited only by statistical noise, records fields down to a fraction of 1 gauss. The heliometric resolution on the disk is about 1′ along the slit, so that the measurement when scanning is an average over a considerable area of the photosphere.

An automatic scanning system shifts the sun's image in a series of parallel traces across the slit of the spectrograph. The dispersion is 1 Å per 11 mm and the resolving power is 600,000. At the focus a double slit is placed on the line Fe I 5250.216. A sensitive, 2-tube, photo-electric detector, balanced to reject common-mode fluctuations, responds only to oscillating

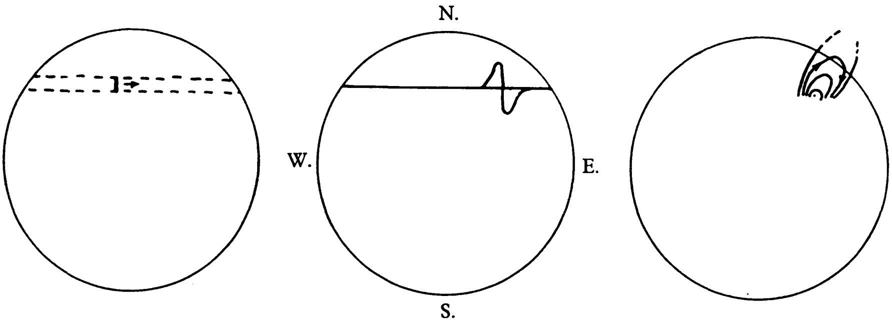

Fig. 1. Response trace of magnetograph as slit scans image.

Zeeman displacements of the line that result from the alternating sign of the electro-optic analyzer in front of the slit. A moving spot on the cathode-ray tube displays the magnetic effects conformally, and the record is photographed with a time exposure.

As we pointed out before (Babcock and Babcock [2]), an upper limit of the order of 2 gauss can be placed on the fields of individual granules by the observation that, with a slit fixed on a magnetically 'quiet' part of the image, admitting light from approximately 100 granules, the root-mean-square fluctuations are no greater than about 0·2 gauss. Hence it appears that equipartition in the sense expected by Alfvén [3, 4, 5] does not occur. For this reason, among others, we believe that the small Zeeman displacements that are measured are properly interpreted as representing the mean of coherent fields, averaged along the slit, apart from the effect of granules.

Fig. 1 shows schematically the type of response. The slit, having a length equivalent to 0·04 of the solar diameter, moves slowly across the image. The response on the cathode-ray tube is an upward deflexion if the field vector is toward the observer, and vice versa. Deflexions are proportional to the component of the field vector in the line of sight, up to several gauss. The trace shown is typical of a BM region. For such a region, we infer that the flux loops are somewhat as shown in the third part of the figure. BM regions commonly appear rather abruptly, and persist for several days, weeks, or months, with more or less associated activity on the disk and in the higher atmospheric layers.

Plate I shows a typical magnetogram with twenty-two parallel traces. The sensitivity here is such that a deflexion of one trace interval is equal to about 1 gauss. Other magnetograms show examples of BM regions and of a UM (unipolar magnetic) region, as well as deflexions characteristic of the poloidal or 'general' field at high heliometric latitudes.

When smaller surface elements are to be investigated, the desirable resolution in time is correspondingly increased, and records repeated at intervals of only a few minutes would be appropriate. But magnetograms taken at a rate of only one a day are adequate for a rough analysis of the magnetic regions of large and moderate size for which the daily changes are often rather minor. Altogether, more than 650 magnetograms have been obtained during the last four years. The data on the distribution, intensity, and polarity of the magnetic flux as it passes through the photosphere, together with the consequences of the fact that div $\mathbf{H} = 0$, enable us to infer a good deal about the disposition of the lines of force above (and perhaps even below) the photosphere. Thus, in examining the magnetograms, one is usually visualizing the magnetic lines of force and attempting to correlate them with material motions and with other phenomena observed either optically or in the radio spectrum.

We can usually regard the highly conducting material of the sun, within any given volume, as identified with the magnetic flux within that volume. In a sense, the magnetic flux serves as a 'tracer', or tag, for the material, enabling us to follow its movements. For example, the appearance of a bipolar magnetic field on the sun where there was none before indicates that material formerly submerged has been brought to the surface, carrying its magnetic flux with it. The lines of force at the surface are comparatively free to loop upward into the region of the corona. Spreading and weakening of the surface fields with conservation of total flux suggests that the associated material is extending itself over a larger portion of the sun's surface, and that the flux loops are rising higher. Magnetic flux and material motions on a large and moderate scale (from $0{\cdot}3\,R$ down to $0{\cdot}03\,R$ or less) may thus be traced. The extension of similar observations to yet smaller turbulent elements is a problem of technique that is capable of much further development.

The observational evidence of the magnetic records is now firm in its major respects, and must be taken into account in the development of theories of the sun's magnetic field, both internal and external.

The principal classes of magnetic patterns observed are those of the main poloidal or 'general' field, the BM (bipolar magnetic) regions, and the UM (unipolar magnetic) regions. Flux patterns of these three types are illustrated schematically in Fig. 2.

1. The general field. Evidence for this is usually found only in high heliographic latitudes, roughly above ± 60°, although the limits are rather variable and indefinite. Polarity has been consistently positive in the

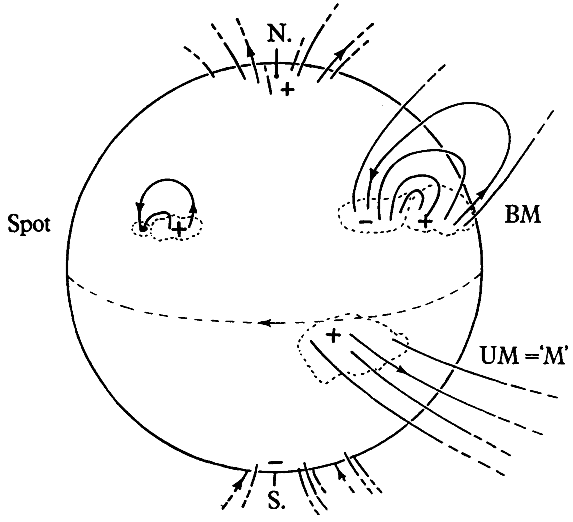

Fig. 2. Schematic representations of magnetic lines of force of (*a*) the general field, near the poles, (*b*) two BM regions, one with a spot, and (*c*) a UM region. Above UM regions, the lines of force are probably carried out to great distances by energetic corpuscular streams expelled from these regions; the lines of force presumably return through widespread areas in which the field is below the limit of detectability.

north, negative in the south. The fine structure is variable. Mean field intensity is of the order of 1 gauss. The coronal features known as polar tufts arise from the same regions, and presumably delineate the lines of force of the general field.

2. BM fields. These are the strongest features of the magnetic records. There are two contiguous areas of opposite polarity. A great diversity is apparent in field intensity, in total flux, and in area. The BM regions often extend towards the poles far beyond the zones of latitude in which sunspots are common. Spots are often found within BM regions, but many BM regions do not contain spots. The preceding and following

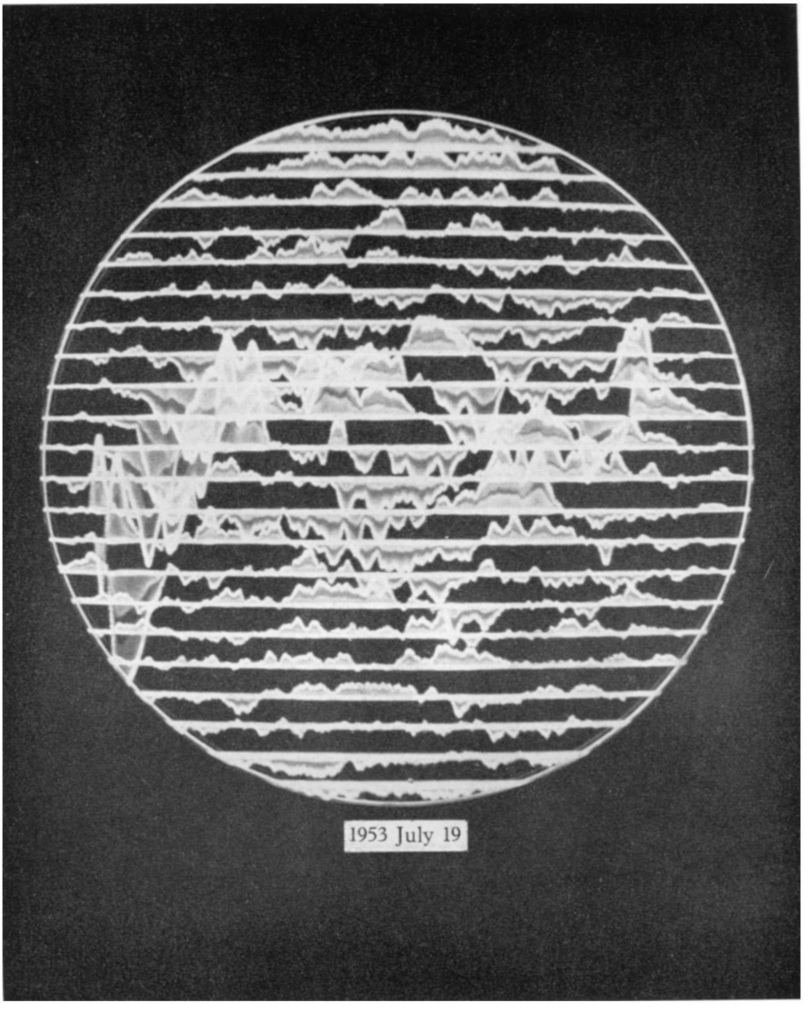

Plate I. Typical magnetograms, showing extensive weak fields.

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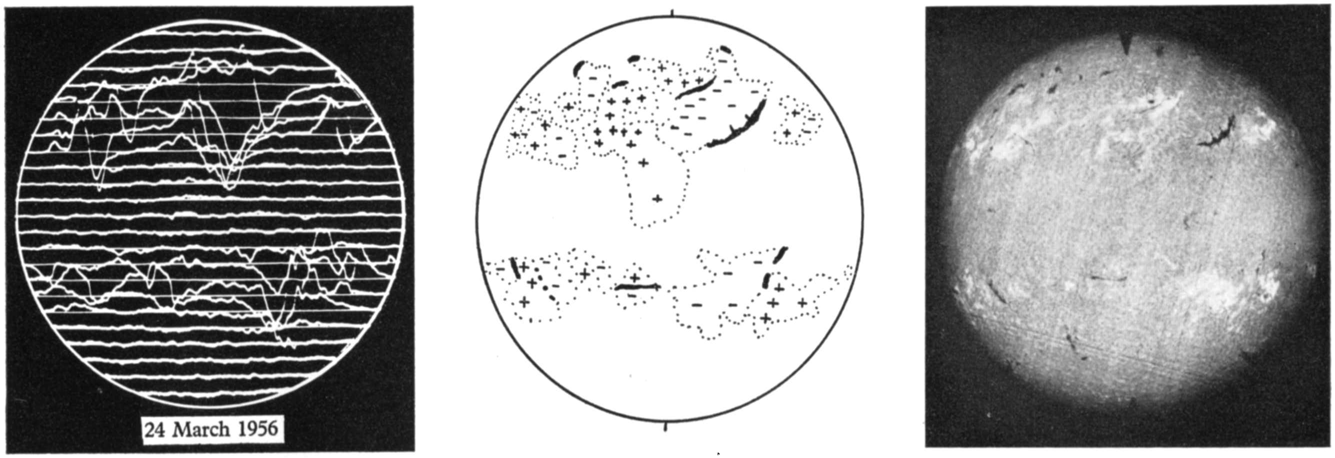

(*a*) (*b*) (*c*)

Plate II. The magnetogram (*a*) has been converted to a diagram (*b*) showing magnetic areas of positive and of negative polarity. From the *H* spectroheliogram (*c*) the stable filaments have been transferred to diagram (*b*) to show their approximate position relative to the magnetic areas.

parts of BM regions obey the laws of magnetic polarity found by Hale to apply to spot groups. The regions originate as if loops of a submerged toroidal field were brought to the surface. The more prominent and concentrated regions, in their early stages, usually develop spots, but the expanding BM fields persist long after the spots have disappeared. Whereever the average field of a BM region is stronger than about 2 gauss, bright Ca II plages appear on the spectroheliograms. A less sensitive indicator of the field is bright $H\alpha$. However, on spectroheliograms of good quality, the small, fine, light and dark $H\alpha$ flocculi that form the fine structure of the chromosphere, and which suggest a random pattern in regions free of any extended magnetic field, take on a coherence of alignment if the mean field is 1 gauss or more. With increasing age, the BM regions tend to expand gradually and sometimes asymmetrically as the field intensity diminishes. At this stage, stable filaments—seen in the light of $H\alpha$—may appear above the surface. These filaments or prominences are usually disposed either across a BM region so as to divide it into two parts of opposite polarity, or they tend to delineate the border of such a region, preferentially on the poleward side, toward which the region is slowly expanding (Plate II). Such bordering filaments are frequent at the present stage of the solar cycle, when the expanding BM regions seem to push the prominences before them into quite high latitudes. Several BM regions are often found to merge into a complicated pattern. Some of the 'softer' BM regions have weak fields and are very extensive, up to about $0{\cdot}3R$; they probably do not develop spots or other marked characteristics of active regions.

There is a general correspondence between the arching lines of force, that, by inference, rise high into the solar atmosphere, joining the positive and negative parts of BM regions, and the coronal regions showing the bright green (λ 5303) and red (λ 6374) radiations reported by the coronagraph observers.

3. UM regions. These are rather extensive regions of only one polarity. The strongest mean fields have been about 2 gauss; areas are of the order of one-tenth of the disk. They appear unrelated to other surface features, and it is not apparent where the emergent magnetic flux returns to the sun. The UM regions are transitory, but the outstanding example could be identified on eight successive rotations of the sun. It occurred in 1953 as the last sunspot cycle reached its terminal stages. We have suggested that, as a class, the UM regions are to be identified with the heretofore hypothetical 'M' regions of Bartels. The best UM regions of 1953, on its central meridian passages, preceded by about 3 days the onset of a series

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of 27-day recurrent geomagnetic storms (Babcock and Babcock [2]). The CM passages of the same region coincided with a series of 27-day recurrent fluctuations in cosmic ray intensity (Simpson, Babcock and Babcock [6]). We infer that the magnetic flux emerging from UM regions forms a coherent bundle (identifiable with a coronal streamer) extending outward into interplanetary space sufficiently far to intercept the earth on occasion. Presumably the magnetic lines of force identified with the streamers are carried out to a great distance by energetic particles expelled from the photosphere.

As we have remarked before, a number of solar phenomena can be qualitatively related to solar magnetic fields on the assumption that corpuscular emission from the photosphere occurs preferentially in regions where there is a coherent magnetic field, whether near the poles, or in the lower-latitude BM and UM regions. Above the photosphere the ionized corpuscular streams are guided by the lines of force or distort them, depending upon the relative magnetic and kinetic energies; they condense, if trapped in sufficient quantity above BM regions, to form the dark filaments. Above UM regions the corpuscular streams are presumed largely to overbalance in energy the associated fields, thus carrying the fields in extended bundles to great distances.

While most of the principal results described here have been reported earlier (Babcock and Babcock [2]), they have gained added weight through the continued accumulation of data since 1954. Furthermore, the existence, polarity, and order of magnitude of the weak general field have been confirmed by a second magnetograph incorporating certain technical improvements and operating with the advantage of the superior sky of Mount Wilson as compared to Pasadena.

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Discussion

Parker: Do you think it might be possible to use your method also to obtain some idea of the magnetic configuration in the vicinity of a solar flare?

Babcock: I think this is much more difficult. As a rule we can get only one or two magnetograms a day. Flares have a short lifetime, and their adequate observation would require improved resolution.

Schlüter: The correlation between the magnetic field and filaments (quiescent prominences)—showing that filaments occur only where the vertical component of the magnetic field disappears—this correlation is exactly that which I had predicted on the basis of my theory of filaments which I have described in the paper by Kippenhahn and myself (the paper will soon be published). Already in 1954 I tried to verify these predictions using the records then available and kindly made accessible to me by Dr Babcock. At that time, however, the geometrical resolution of the magnetograph was not quite sufficient to give an unambiguous check.

Lehnert: Just let me make some comments on the coupling between a turbulent magnetic field and the density fluctuations. Alfvén has argued that, due to this coupling, the measurements may not give the proper value of the magnetic field at the solar surface. Have I grasped it correctly that the resolution of your instrument corresponds to a region containing about 100 granules?

Babcock: Yes, when the slit is held stationary on the image.

Lehnert: Then, let us suppose that the total magnetic field, $\mathbf{B}=\mathbf{B}_0+\mathbf{b}$, in such a region, D, consists of a homogeneous general field, $\mathbf{B}_0$, and a turbulent field, $\mathbf{b}$. The probability of picking out a sub-region inside D with the field $\mathbf{b}$ in the range $db_x db_y db_z$ is defined by $f db_x db_y db_z$, where f is a normalized distribution function. Further, for the sake of simplicity, we do not include temperature fluctuations and assume that only the density $\rho=\rho(B_x, B_y, B_z)$ is coupled with the magnetic field. The total contribution to the measured Zeeman effect gives a measured mean of the magnetic field

$$\overline{B_z}=\frac{1}{\rho_0}\iiint_{-\infty}^{+\infty}\rho B_z f db_x db_y db_z,$$

where the z-axis has been chosen along the observation line and ρ_0 is the density in absence of turbulent fluctuations. Introducing the excess density $\rho'=\rho-\rho_0$ we may also write

$$\overline{B_z}=B_{0z}+\frac{1}{\rho_0}\iiint_{-\infty}^{+\infty}(\rho' B_z+\rho_0 b_z) f db_x db_y db_z.$$

There is no doubt that the measurements give the proper value, $\overline{B_z}\approx B_{0z}$, when the field B_0 is strong (as in sunspots) and $|\rho'/\rho_0|\ll 1$ as well as $|b/B_0|\ll 1$. On the other hand, if the general field $\mathbf{B}_0$ disappears it is easily seen that also B_z disappears. Consequently, I should think that your measurements show that there *exists* a general magnetic field of the sun, regardless of Alfvén's mechanism being of importance or not. But, what I should like to point out is that it has so far not been proved that the effect of turbulent coupling can be neglected.

Babcock: If this systematic coupling is significant, would not a bias be observed when the magnetic field is measured over the whole solar surface?

Lehnert: Not necessarily. Suppose that the measurements are compared in two regions, D_{I} and D_{II}, on the solar surface, equally distant from the equatorial plane and situated on the same meridian circle as in Fig. 3. The general magnetic field is assumed to be symmetric around a vertical axis in the figure. When comparing the measurements in D_{I} and D_{II} the observer is imagined to rotate around the line of sight when observing D_{II}. The rotation is carried out such as to bring the general field in D_{II} in a direction anti-parallel to that in D_I (open arrow).

Now, if the current density is reversed at every point within the whole configuration the density distribution can be assumed to be unchanged. Thus, the density has the property

$$\rho(B_x, B_y, B_z) = \rho(-B_x, -B_y, -B_z).$$

Further, the turbulent field $\mathbf{b}$ is assumed to be axisymmetric with respect to the magnetic field direction, i.e.

$$f = f[\hat{\mathbf{B}}_0 . \mathbf{b}, |\hat{\mathbf{B}}_0 \times (\mathbf{b} \times \hat{\mathbf{B}}_0)|]; \quad \hat{\mathbf{B}}_0 = \text{unit vector of } \mathbf{B}_0.$$

We have to distinguish between two cases, namely:

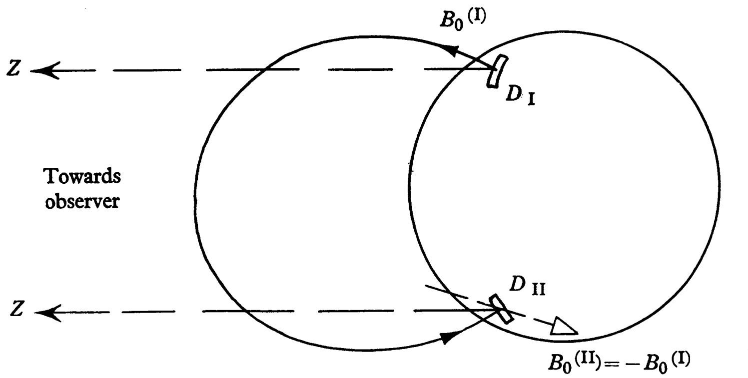

Fig. 3. Measurement of the Zeeman effect in two regions, D_I and D_{II}, of the sun equally distant from the equatorial plane and situated on the same meridian circle. The observer is situated approximately in the equatorial plane. The general magnetic field $\mathbf{B}_0$ is assumed to have a dipole-like shape.

1. The turbulent intensity is the same in D_I as in D_{II}. This applies, e.g. when the turbulence is *homogeneous* all over the solar surface. In such a case the spectral functions f_I and f_{II} in D_I and D_{II} are equal ($f_I = f_{II} = f$). The proper fields are $\mathbf{B}_0^{(I)} = \mathbf{B}_0$ and $\mathbf{B}_0^{(II)} = -\mathbf{B}_0$, respectively, and the measured fields are $\overline{B_z^{(I)}}$ and

$$\overline{B_z^{(II)}} = -\frac{1}{\rho_0} \iiint_{+\infty}^{-\infty} \rho(-B_{0x} - b'_x, -B_{0y} - b'_y, -B_{0z} - b'_z)(-B_{0z} - b'_z)$$
$$\times f[-\hat{\mathbf{B}}_0 . (-\mathbf{b}'), |-\hat{\mathbf{B}}_0 \times (\mathbf{b}' \times \hat{\mathbf{B}}_0)|] \, db'_x \, db' \, db'_z = -\overline{\mathbf{B}_z^{(I)}},$$

where we have introduced $\mathbf{b}' = -\mathbf{b}$. Consequently, no bias exists in the homogeneous case.

2. However, if the distribution of the turbulent magnetic intensity over the solar surface is *inhomogeneous* in the sense that $f_I \neq f_{II}$ it also follows that $\overline{B_z^{(I)}} \neq -\overline{B_z^{(II)}}$, and a bias exists.

To sum up, the non-existence of a bias may be explained in two ways. Either does it indicate that Alfvén's mechanism is unimportant, or it implies that the intensity of the turbulent magnetic field is distributed homogeneously over the solar surface.

Alfvén: Professor Cowling has already touched the problem in his introduction yesterday when he said he was inclined to accept observational evidence and that I was questioning observational facts. The observational facts, which Babcock has obtained in an admirable way, consist of a line displacement—that is the observational fact—and I have not at all questioned that. But in order to have the right to put 'magnetic field' instead of 'line displacement' into the resulting diagram one has to use Zeeman effect theory, i.e. the behavior of a single atom, and one also has to use magneto-turbulent theory of the photosphere. Only by using these two theories is it possible to infer anything about magnetic fields. Because a magneto-turbulent theory does not exist at present it is impossible to infer anything about magnetic fields. What Lehnert has pointed out now shows that such a theory is very complicated and we are very far from being able to say anything definitely. I am not at all trying to sketch such a theory but just let me point out the following. Suppose that a general magnetic field of say 10 gauss or perhaps even less is superimposed by a turbulent field of 200 gauss. In some regions the turbulent field is, roughly speaking, in the direction of the external field, in other regions it opposes the external field. Even a very weak coupling with density or intensity of spectral lines could result in a pronounced systematic effect, provided that the turbulent magnetic field is strong enough.

Yesterday, in the discussion on stellar magnetic fields Dr Babcock pointed out that the measured average field could differ from the true average. A systematic coupling of this type could be effective.

Cowling: To explain the discrepancy between the fields estimated by Babcock and those required by Alfvén, it is not sufficient simply to show that turbulent fields may affect the field estimated from observation. In Alfvén's case it is necessary also to show that the effect is regularly to reduce the observed field and not to increase it, i.e. that the sign 'goes the right way'. Objections to the observed value based on the inadequacy of theories of magneto-turbulence cut two ways. I personally do not find the arguments in favor of a turbulent magnetic field of order 200 gauss in the photosphere altogether convincing.

Lehnert: I should like to emphasize that in my comments I have said nothing about the sign of the difference $\overline{B}_z - B_{0z}$. The only thing I want to point out is that this difference hardly vanishes identically and that a non-existence of a bias cannot be used as an argument against Alfvén's hypothesis.