INVITED DISCOURSES

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INVITED DISCOURSE A

given to participants in the General Assembly at $21^h\ 00^m$ on Wednesday 26 August 1964 in the Auditorium Maximum of the University of Hamburg, by

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on

SOLAR MAGNETIC FIELDS

1. INTRODUCTORY REMARKS

The discovery of magnetic fields on the Sun made by George Ellery Hale in 1908 (**1**) is undoubtedly one of the most outstanding events in the astronomy of this century. It is well worth mentioning that the geomagnetic field was a unique example of cosmical magnetic fields before this discovery. But during the last two decades, it became known through Babcock's work (**2**) that numerous stars have also magnetic fields amounting to several thousand gauss on the average over the star's surface and thus considerably exceeding solar magnetic fields concentrated mainly in sunspots.

If, therefore, we were able to examine our Sun as a star, from outside the solar system, the solar magnetic fields could hardly have been detected, since the magnetic regions contribute less than 0·1% to the total brightness.

Since Hale's discovery more than half a century has elapsed and a great deal of data has been accumulated about solar magnetic fields and their behaviour. Nevertheless the nature of solar, as well as stellar, magnetic fields remains one of the greatest mysteries in science. The theory of the phenomena is still almost non-existent, and the observations sometimes lead to controversial conclusions. For instance, theoretically a stellar (or solar) magnetic field should not practically be decaying because of very high conductivity and very big linear dimensions in the stars; but, on the other hand, observations frequently show strong spasmodic changes of the magnetic field accompanied by other violent events in the state of the stellar plasma. Huge, extremely rapid, changes of magnetic field in magnetic variable stars are observed; complete redistribution of the field, and even reversal of polarity, takes place during a period of one day. Also the role of magnetic forces can hardly be over-estimated; as an extreme example consider such a star as HD 215 441 where Babcock found a field strength of 34 kilogauss. The magnetic pressure here can reach 50 atmospheres, which is extremely large compared with the ordinary gas and radiation pressures in stellar atmospheres.

The problem of element abundances is also related very closely to magnetic fields. The extremely long time of diffusion needed for the mixing of elements in the presence of magnetic fields does not make it improbable that the chemical composition of the magnetized ropes or flux tubes could be different from the rest of the star. From this point of view, it might be worth considering carefully the chemical composition of sunspots in comparison with the composition of the undisturbed photosphere. In principle, sunspots, as Alfvén suggested (**3**), can keep the memory of a distant past composition, being a kind of reliquary of the early stage of evolution of our Sun.

The present discourse does not pretend to be complete; it is rather a moderate attempt to present to your attention some aspects of our observational knowledge about solar magnetic fields. Theories are considered only occasionally, for the simple reason that it would be difficult for the author, who is mainly an observer, to present both aspects in one discourse with equal completeness and quality.

2. SOME REMARKS ON OBSERVATIONAL TECHNIQUES

As you know, the first observational evidence of solar magnetic fields was obtained by Hale from the phenomenon of the splitting of dark iron lines in the spectrum of sunspots. The lines were split in the same way as the emission lines of evaporated metals in a discharge tube placed between the poles of a strong laboratory magnet. This phenomenon, well known in physics as the Zeeman effect, has been used since then for the examination of solar and stellar magnetic fields by optical methods.

As is well known, in the simplest case of a pure longitudinal (along the line of sight) magnetic field we have two circularly-polarized components of the spectral lines, and in the case of a pure transverse field of the same strength we have in the same place two plane, equally polarized, components and one further plane-polarized at right angles to these in the middle.

Strong magnetic fields concentrated inside sunspots are usually estimated visually or photographically by measuring the distance between the components of the split lines and Figure 1 shows a photograph of Zeeman splitting in the spectrum of a sunspot, taken with the simplest polarizing optics ($\frac{1}{4}\lambda$-plate plus polaroid), permitting to eliminate one of the components. However, the sensitivity of this method is comparatively low—usually about 100–200 gauss—and the method is not efficient for continuous record of magnetic fields over extensive areas.

A great advance in the photographic method has recently been made by Leighton (4) who used a spectroheliograph with polarizing optics, thus converting the magnetic fields to photographic densities. Although the sensitivity is not very high, the method allows the practically instantaneous determination of the distribution of the magnetic field over the whole solar disk. Another important development has been recently made by Michard (5) by using the jumping slit method first introduced by Deslandres for measures of radial velocity. This method enables an extended region on the Sun to be covered by photographic images of the Zeeman pattern. To avoid the errors of the photographic method many complicated and ingenious interferometric devices have been elaborated by Thiessen, Öhman, Babcock, Treanor and others (6–8, 9). However, the photo-electric method first introduced by Kiepenheuer (**10**) has been found most efficient in this way; this method was developed to its highest efficiency in a magnetograph realized in 1953 by H. W. Babcock (**11**). The essence of the photo-electric method is simple. When the magnetic fields are weak the components of the Zeeman pattern are mutually blended heavily due to finite width of the spectral lines, and the separation between them is not practically measurable. However, if we can modulate the state of polarization of the falling beam, for instance by rotation of polaroid, fluctuations of intensity in the blended Zeeman pattern appear and the photo-electric amplitude of these fluctuations depends in some way on the strength of the magnetic field. The most convenient and efficient method of modulating the state of polarization of the solar beam is to make it pass through a crystal of ammonia phosphate, to the front and back sides of which an alternating voltage is applied thus producing the desired phase retardation in transmitted light. The polaroid introduced besides this crystal transmits only light of one definite state of polarization. In the Crimean Observatory this whole device has been at work since 1956 as an analyzer of circular polarization to record longitudinal magnetic fields; since 1959 it has also been used as an analyzer of plane polarization to record transverse components of magnetic fields (**12**, **13**). The photo-electric method demands the use of a high-dispersion spectrograph and of a good signal-to-noise photo-electric photometer. Apart from those at Mt Wilson and the Crimea, magnetographs are at present at work in the Fraunhofer Institut (**14**), at the Institute of Earth Magnetism (near Moscow) (**15**) and at Pulkovo (**16**).

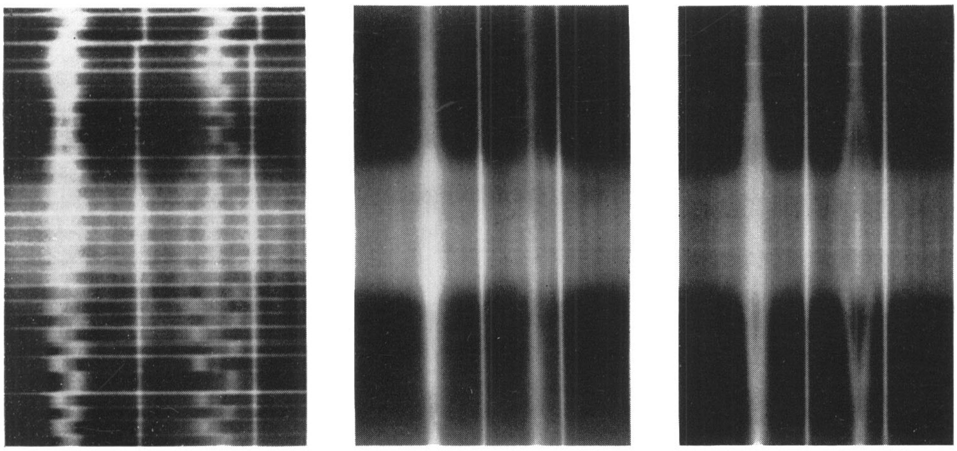

Fig. 1. Zeeman effect in the spectrum of a sunspot.

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The first systematic use of the magnetograph by H. D. and H. W. Babcock (**17**) revealed many important features of solar magnetic fields, although the resolving power of their records was comparatively low—only 70″. This involves a great deal of averaging and smoothing out of the features of magnetic fields, if fine detail is present. We have been able in the Crimea to reduce this effect considerably, by 50 times at least, to extend Babcock's principle of the magnetograph to measurements of transverse fields, and to avoid the unwanted influence of light intensity on the measurements of the magnetic field. We shall see that the influence of resolving power on the results and conclusions about magnetic fields can hardly be over-estimated; and the first example of this influence may be seen from the examination of the general magnetic field of the Sun.

3. THE GENERAL MAGNETIC FIELD OF THE SUN

Figure 2 represents an attempt to compile all the results of the measurements of the general polar magnetic field of the Sun, starting with the first spectroscopic observations of Hale and his co-workers (**18**), who found that the Sun is similar to an uniform magnetized sphere with magnetic axis slightly inclined to the axis of rotation (Positive values indicate that the field is anti-parallel to that of the Earth). Here, all the Mt Wilson determinations (Langer (**19**),

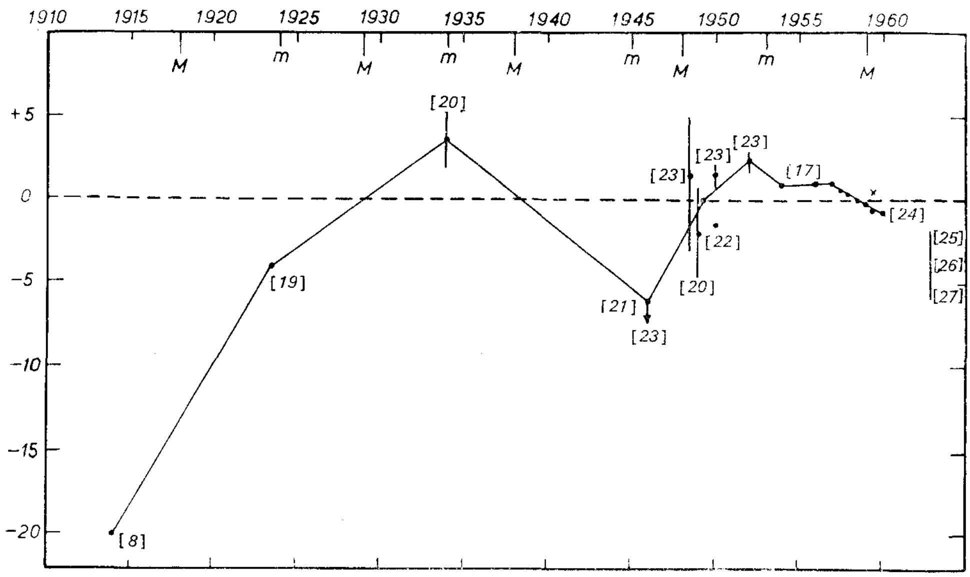

Fig. 2. The variations of the general (polar) magnetic field with time.

Nicholson (**20**), H. D. Babcock (**21, 24**)) are included; the interferometric measurements of von Klüber (**22**) and Thiessen (**23**) and the photo-electric determinations by H. D. and H. W. Babcock (**17**) are also used. The last points represent quite recent determinations made at Mt Wilson (**25**), Cambridge (**26**) and Crimea (**27**); they show quite definitely that, from 1961 up to the present time, the general polar field at the southern pole is absent and that only a weak, but quite appreciable negative (southern) field with a strength of several gauss is fixed at the northern pole.

We see that the epochs of the maximum of solar activity, denoted by M, practically coincide with the reversals of polarity of the polar field, while the minima are in phase with maximal

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positive or negative fields (except for the first determination (**18**)); the coincidence of the reversal in 1957–58 with maximum M was first pointed out by Waldmeier (**28**). Therefore, the possibility that the general polar field is changing with a period of 20–22 years in the same way as sunspot polarity does seem to be reasonable.

A possible explanation of these variations has been proposed recently by H. W. Babcock (**29**). It starts with an axi-symmetric dipole general field with lines of force running entirely in meridian planes. Assuming that the submerged part of each line of force is relatively shallow, we observe that the same line of force is intersected by different surfaces of constant angular velocity arising from the differential rotation of the Sun. As the line of force is frozen into the fluid this results in it being more and more elongated to the west, and, with the further action of differential rotation, the lines of force of an original dipole field become wrapped along the equatorial belt of the Sun. In this way the so-called toroidal field can be created and amplified. The flux ropes can emerge on the solar surface in the form of loops, due to buoyancy and to the fluctuations of density inside these ropes. The process is illustrated in Figure 3. In the final stage the peculiar interaction of the sunspot field with the original poloidal field leads to the destruction of the original polar field and to the formation of a new one with opposite polarity. The model is similar to a freely running oscillator with a 22-year period, maintaining the energy of the oscillations from the energy of differential rotation.

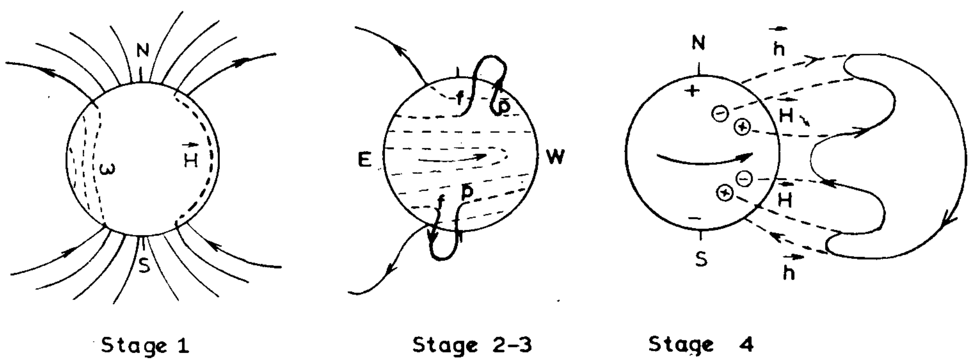

Fig. 3. Illustration of formation of flux loops.

However, despite the attractive features of Babcock's theory, we should consider more carefully the original observational background, and particularly those data which relate directly to the nature of the general field of the Sun. The first question we would like to discuss is the influence of resolving power—a question which may look highly technical at the first glance. Figure 4 shows the original routine records of the polar field we are making in the Crimea with the comparatively high resolving powers of 5″ and 9″. The most important aspect of these records is the *fine structure* of the polar field, the concentration of magnetic fields in separate elements—bundles or ropes, of lines of force with size comparable with the resolving power. Careful examination of such records shows that the similarity of successive records is violated appreciably even if they are only 5″ apart; thus only about 50% of all magnetic elements seen on one scan can be identified on the next one, indicating that about 50% of the elements carrying magnetic fields are less than 5″ in size. In other words, we record two completely incoherent patterns at the same time if we use wider slits or a resolving power of less than 10″.

We see that there are *no uniform* polar magnetic fields at all, but we have instead magnetically-spotted regions containing small elements of different polarities, and only the averaging over the large area indispensable at the low resolution can produce the predominance of the one polarity over the other as if it were a uniform field of one sign (perhaps this spottedness of the field could explain the discrepancies in the early determinations of the magnetic field made at the same time). Figure 5 sheds more light on the problem discussed. Here we have repeated records of the same place near the northern pole ($\varphi = 60°$) made with different resolving

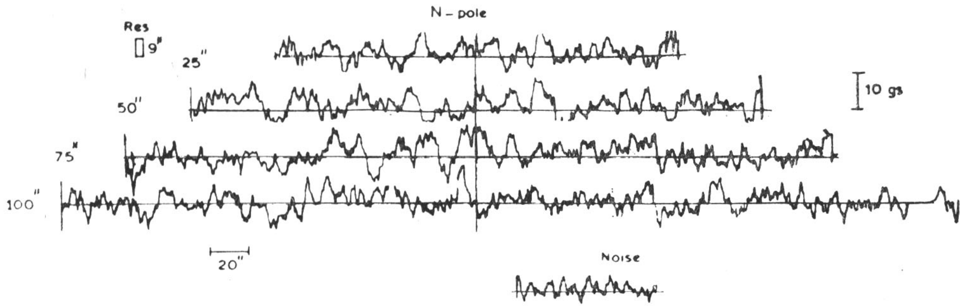

Fig. 4. The original records of the polar field.

powers, 4″ – 5″, 9″ and 27″. In the same figure, the run of maximal field strength and of the number of resolved elements is given, from which we can see that if maximal strength at low resolution is several gauss, it can reach 40 gauss at the higher resolutions. The number of elements can increase by 1·5 to 2 times when we pass to higher resolving powers. The elements

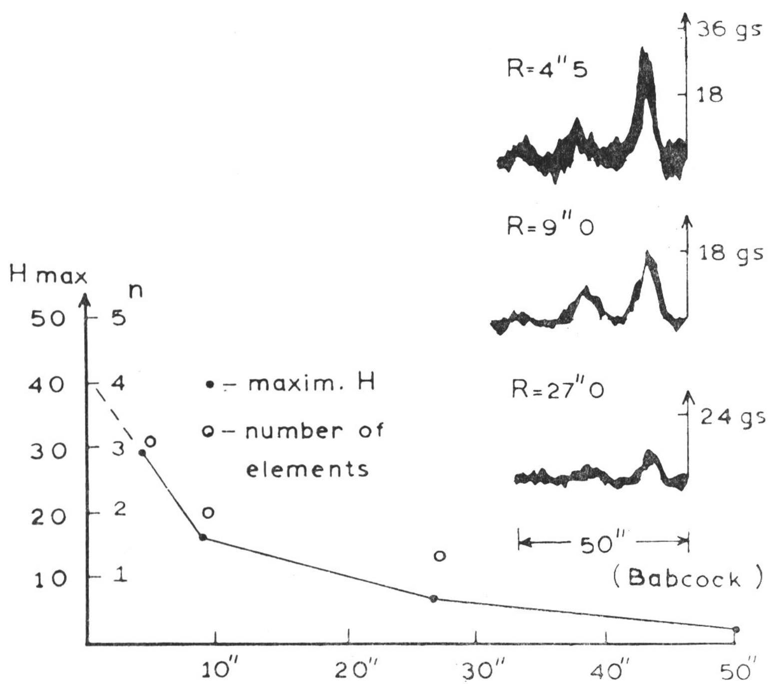

Fig. 5. The influence of resolving power on the strength of the general field and the size of its elements.

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of the general magnetic field appear to be considerably stronger, and of smaller dimensions, than has been previously thought. This conclusion also follows from the so-called power spectrum—the distribution of magnetic-energy fluctuations with the size of elements derived by Howard (**30**), which shows an increase of power for the smaller sizes. The mean amplitude (r.m.s.) of these fluctuations is $\pm 8{\cdot}2$ gauss for the smaller elements in a magnetically-quiet region. In the polar regions, this value can be smaller by a factor of 2.

The magnetic elements that we are considering are relatively stationary formations. According to our observations, there are no appreciable changes in their size and field strength for periods of 4–5 hours and even longer, and the life-times of 10 hours mentioned by Leighton for the elements of supergranulation can also be appropriate in this case.

The one-to-one correspondence between the positions of the magnetic elements and the calcium bright features (Ca II granulation, plages) is one of the most reliable and well-established observational results in the study of the correspondence between solar magnetic fields and the features of the solar chromosphere. The role of Mt Wilson Observatory (H. D. and H. W. Babcock, (**17**), Howard (**31**), Leighton (**4**)) in this field can hardly be overestimated. In particular, Howard and Leighton showed that this correspondence holds true up to the smallest bright features seen at the limit of the resolving power, and the correlation coefficient reaches 0·999 even for the smallest fields of about 2·5 gauss. This circumstance, remarkable by itself, shows that magnetic fields are not the accompanying feature of calcium plages, but rather the reverse; the calcium chromospheric network and plages are indispensable consequences of the action of the magnetic fields. The correlation between brightness and field strength found by Stepanov (**32**) in the Crimea is additional evidence in favour of this statement.

Does this mean, however, that the magnetic fields penetrate into the upper layers of the solar atmosphere, or not? Some information in this direction can be obtained from the comparison of magnetic fields recorded in the photospheric iron line and in the chromospheric core of the Hβ-line (corresponding to a height of 1500 km above the chromosphere). Figure 6 illustrates one of numerous examples of such a comparison, showing a very close correspondence between the magnetic features in the case of an active region with a strong magnetic field. We can trace this correspondence up to the noise level in Hβ (which is about 25 gauss), and there are practically no features in the chromospheric field which cannot be identified in the photospheric field, but not all of those in the photospheric field can be found in chromospheric relief due to low sensitivity of Hβ to magnetic fields. (The magnetic flux through the same area is usually half as large in Hβ as in the photosphere). Although this relates to strong fields larger than 50 gauss, it is tempting to conclude that everywhere ropes and bundles of lines of force, coming out of the photosphere more or less radially, penetrate into the chromosphere and probably even higher, and that the coronal fine structure in quiet regions could also be closely connected with these fields. It would be interesting to examine carefully whether such a connection exists or not. It is also very probable that the Hα-chromospheric reseau observed through the Hα-pass-band can follow closely the magnetic relief of the general field as Menzel and Moreton suggest (**33**).

I would like to draw your attention to one new peculiar feature which relates directly to the geometry of the general magnetic field. If we compare carefully the positions of the calcium plages and the bright knots of the calcium network with the positions of the corresponding magnetic hills on the photospheric relief, we observe that most of Ca II features are shifted a little to the east relative to the position of the magnetic hills. The *same* shift is found for the Hβ magnetic details when comparing them with the photospheric ones. The effect is small, about 3″, but quite appreciable. This phenomenon has much in common with the inclination of the magnetic axes of uni-polar sunspots to the east observed by Bumba (**68**). Consideration of all possible factors which can eventually lead to this effect shows that the only probable cause is the action of the Coriolis force on the vertical ropes of lines of force along which chromospheric gases are streaming downwards, according to the observations of St. John (34), Leighton (35) and others. The eastward tilt of these ropes is not high, but can reach 30°–40° at some point.

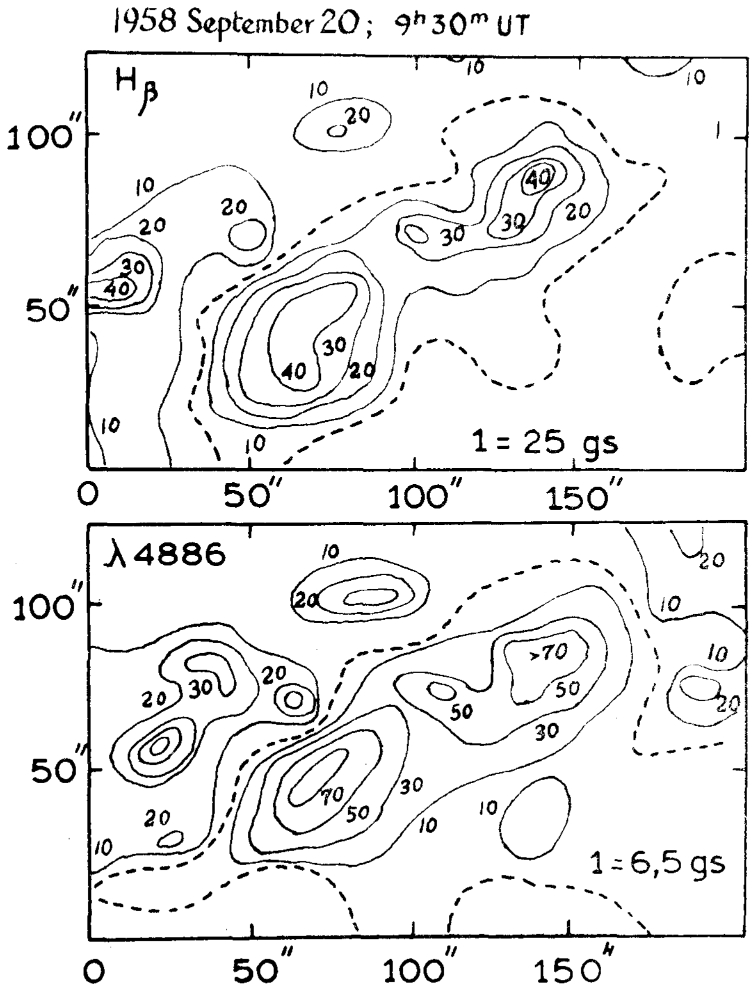

Fig. 6. The comparison of photospheric and chromospheric magnetic fields.

Thus the general field, when looking from the pole of the ecliptic, looks like the needles of a porcupine, or like a tufted brush face upwards in the ecliptic plane.

In concluding our discussion of the general magnetic field let us consider what information we can get about the nature of this field from the routine observations of the polar caps. Figure 7 shows the results of such an averaging procedure made separately for each latitude at the north and south poles. The records have been obtained in the period August 1963 to June 1964 at the Crimean Observatory with a resolution of 9″. Quantitatively, Crimean results are in agreement with those obtained at Mt Wilson and Cambridge, but we should like to draw your attention not only to the quantitative but also to the qualitative aspect of the phenomenon.

The original records (see figure 4) show distinctly the predominance in the number of south-pole elements in the northern polar cap, while at the southern polar cap there is no such excess, although the field of 0·5 gauss still can exist in the southern polar cap. The most striking feature is the *independence* of the mean field strength of the longitudinal field $H_{\parallel}$ (which is about 1·3 gauss) on latitude, while it should follow the law $H_{\parallel} \simeq C \cos\varphi$, ($C$ being constant $= \frac{2a}{R^3}\sin\varphi$, for φ greater than 60°) if the polar field were a dipole field. In other words the real polar field is not similar either to a dipole field or to that of a uniform magnetized sphere.

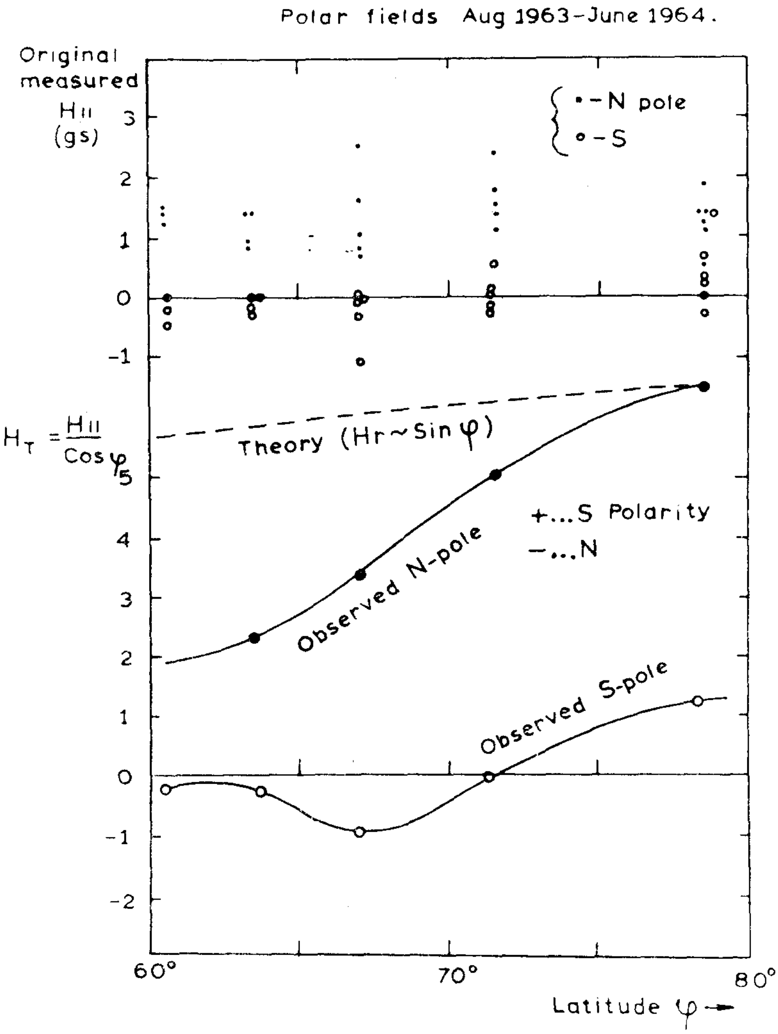

Fig. 7. The dependence of the solar polar field on latitude.

The inconsistency of the dipole representation, the fine structure and spottedness of the field, the disappearance of the resultant field in one of the poles for a long time—all these discouraging facts are at the same time very stimulating, and they probably call for some new concepts in the theory of solar and stellar magnetic fields.

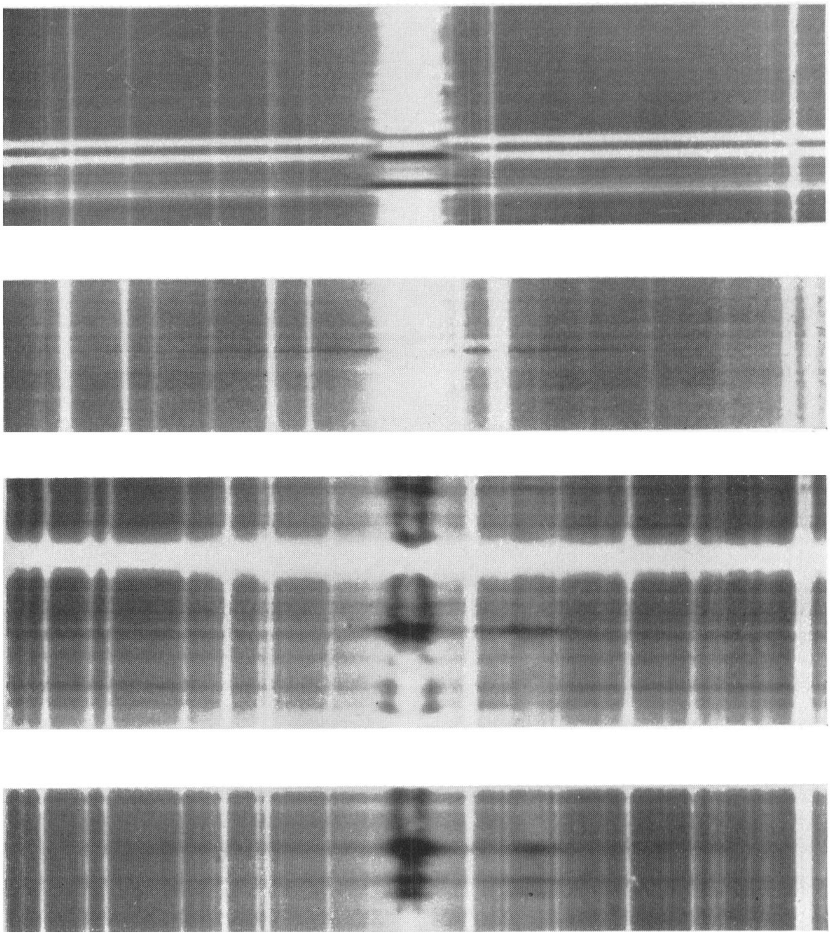

Fig. 8. The fine structure of emission in active regions on the Sun.

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4. STRONG MAGNETIC FIELDS AND ACTIVE REGIONS ON THE SUN

From all we have said about the general magnetic field, we can conclude that fine structure should probably be the common feature of solar magnetic fields in general, and it seems reasonable to look for this property in the strong magnetic fields observed inside sunspots and groups of spots or, more generally, within active regions. A further reason to expect fine structure of the magnetic fields inside active regions should probably be mentioned—it is the phenomenon of fine structure of emission in active regions. This phenomenon has been under examination for a long time in the Crimea (1954–1959, (36)) and very roughly it can be described as follows. With good seeing and at the highest available resolving power, the emission in active regions, independently of the particular phenomena observed (flares, moustaches, flocculae), is concentrated in small grains, their size being at the limit of resolution (0″·5), the emission being generated in separate spectral lines or in the continuum. Examples of this phenomenon are illustrated in Figure 8. The trouble with this fine structure of emission has been how to explain

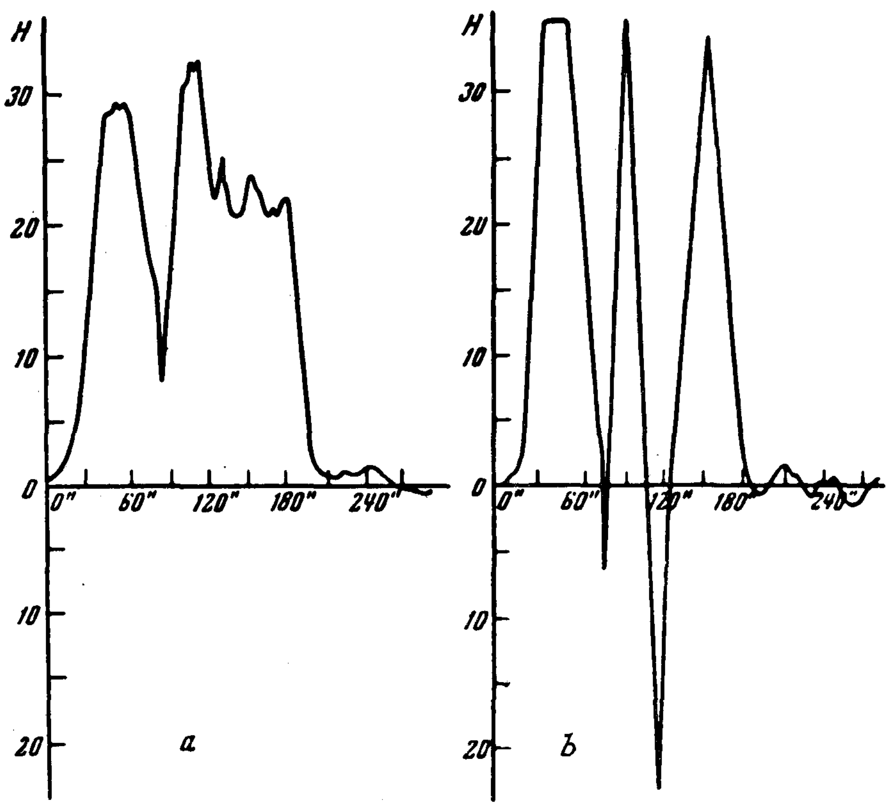

Fig. 9. The influence of resolving power on the character of the magnetic field in an active region.

the great losses of energy observed from such small grains, and we can now see that the only source must be magnetic energy. But in this case magnetic fields must also possess a fine structure. Consideration of the records of magnetic fields made with different resolutions shows that somewhere we can always find elements of the field comparable in size with the resolution (2″ – 5″), and that the field gradients can be increased by a factor of 10 or more at a higher resolution (5″) than that usually adopted (50″). Figure 9 illustrates how a so-called unipolar region at low resolution is converted into a multipolar region at high resolution.

Let us now consider the fine structure of magnetic fields more closely in the case of sunspots. As we know, the magnetic fields are, according to Hale, here similar to the field of the top of a solenoid. However Evershed first observed (37) transverse fields inside the actual umbra of sunspots. We have frequently observed, with good seeing, small inclusions of the transverse field inside sunspots of only one polarity and these formations are observed practically in the same places where moustaches appear (38). Figure 10 illustrates these inclusions. The next

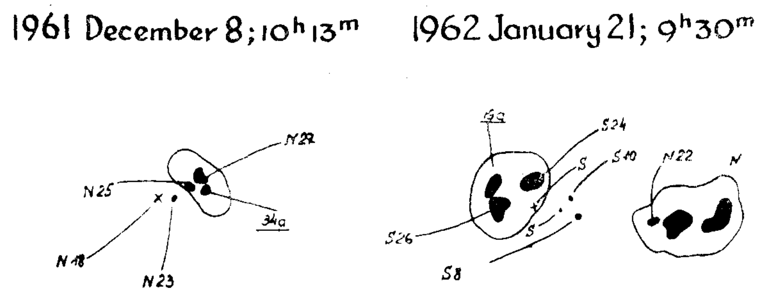

Fig. 10. The inclusions of transverse fields into uni-polar regions.

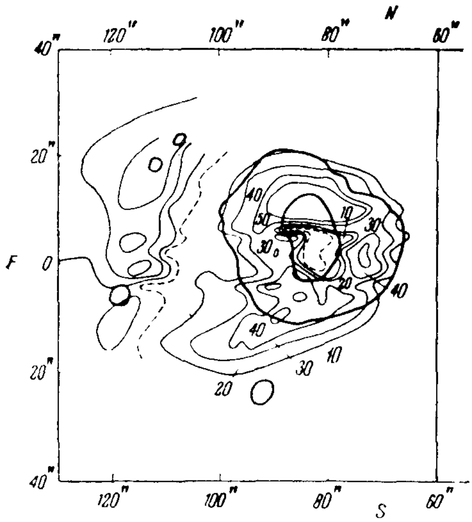

Fig. 11. The fine structure of the magnetic field inside a big sunspot.

example, shown in Figure 11, is the magnetic relief of the fine structure of a longitudinal field inside a very big spot. In a very small area inside the actual umbra, the field drops to zero, separate peaks of size about 2″ are also clearly seen inside the spot, thus pointing to a strong *inhomogeneity* of the field (39). Although the average field strength according to the photographic Zeeman splitting was 4000 gauss, we do not know the peak values, and values twice as large are not, in principle, excluded. If further examination permits us to establish the existence

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of such fields we probably would feel more comfortable in attempting to explain the origin of solar cosmic rays.

We can also obtain fresh information from a study of transverse fields, and Figure 12 illustrates *directional* inhomogeneity inside sunspots. The most important factor here is the very rapid rotation of the field vector $H_{\perp}$ as we pass from one point to another across the disk.

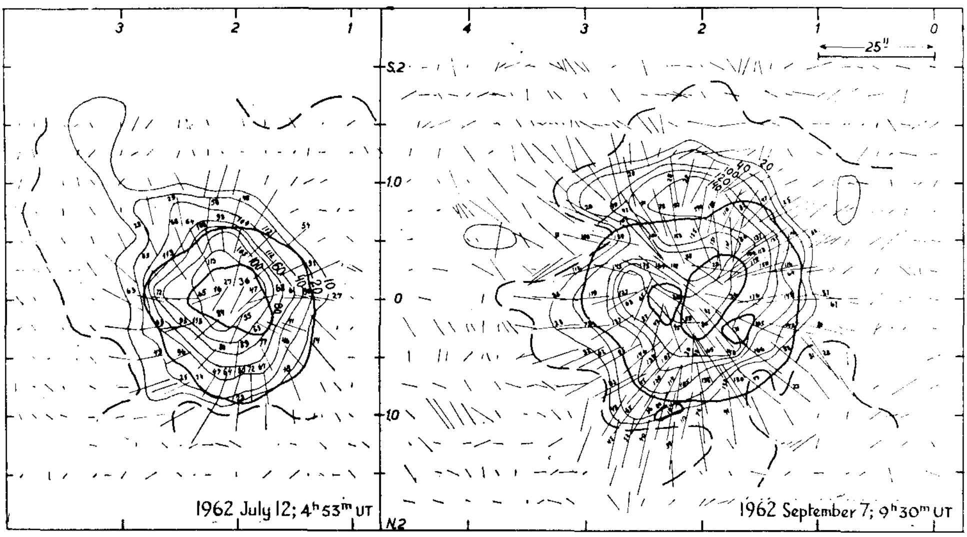

Fig. 12. Examples of rotation of the magnetic vector across the disk.

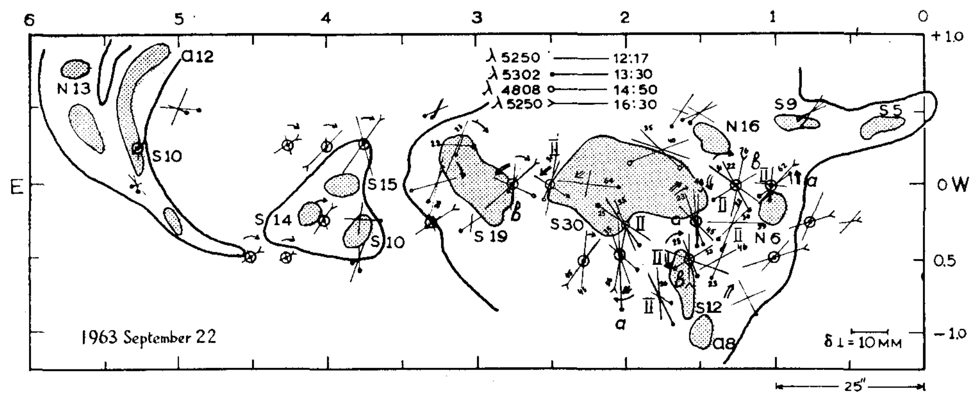

Fig. 13. The rotation of the magnetic vector with depth.

This fact implies the expectation of such rotation also with depth. Depth-dependence can obviously be examined if for magnetic records we use different lines originating at different levels in the solar atmosphere; or, what is less efficient, we may use different parts of the same line. We have recently found very strong rotation of the field vector inside active regions, reaching 90° per 100 km of depth; Figure 13 illustrates the effect (this effect can explain why we

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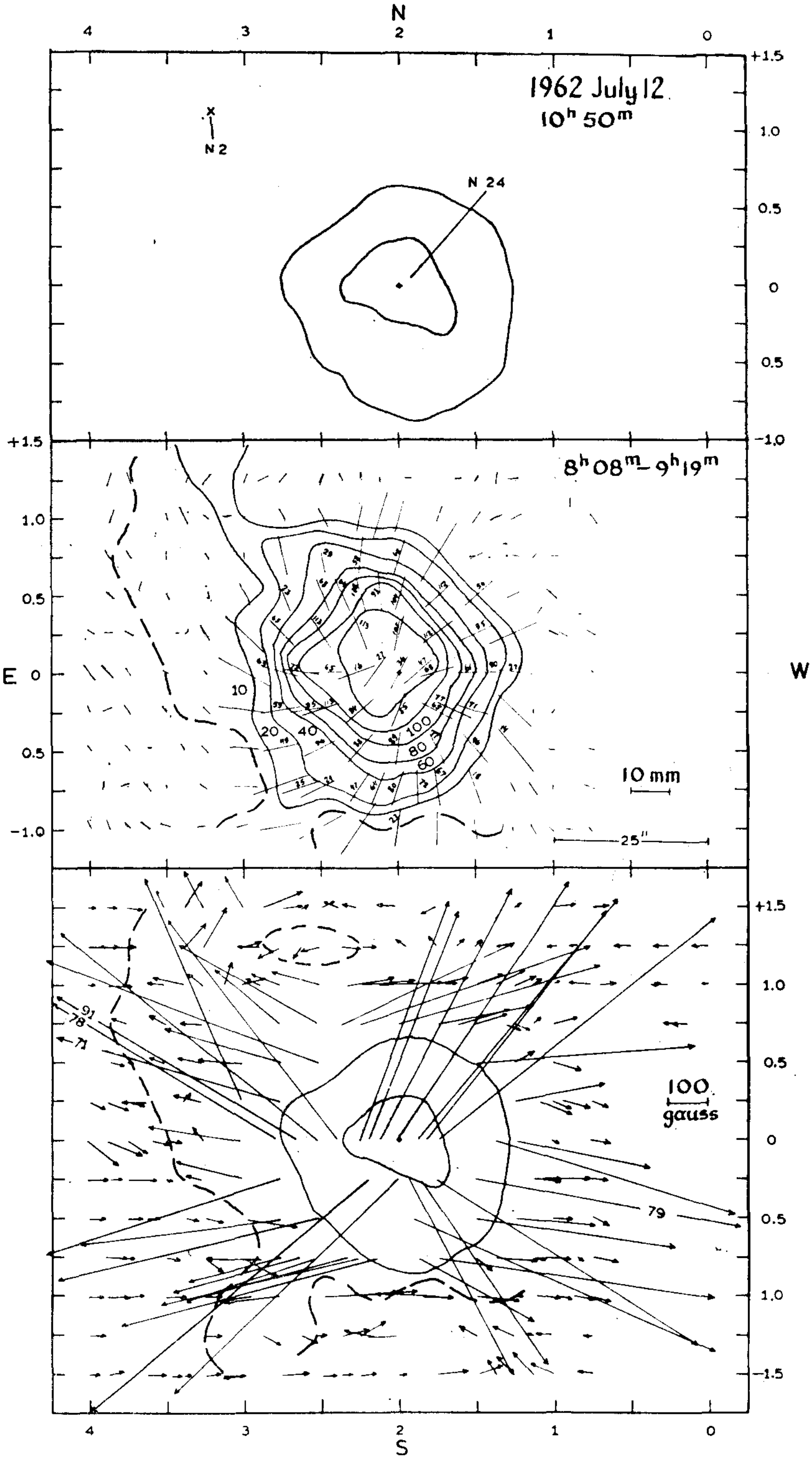

Fig. 14. The spatial distribution of the magnetic vector inside a sunspot.

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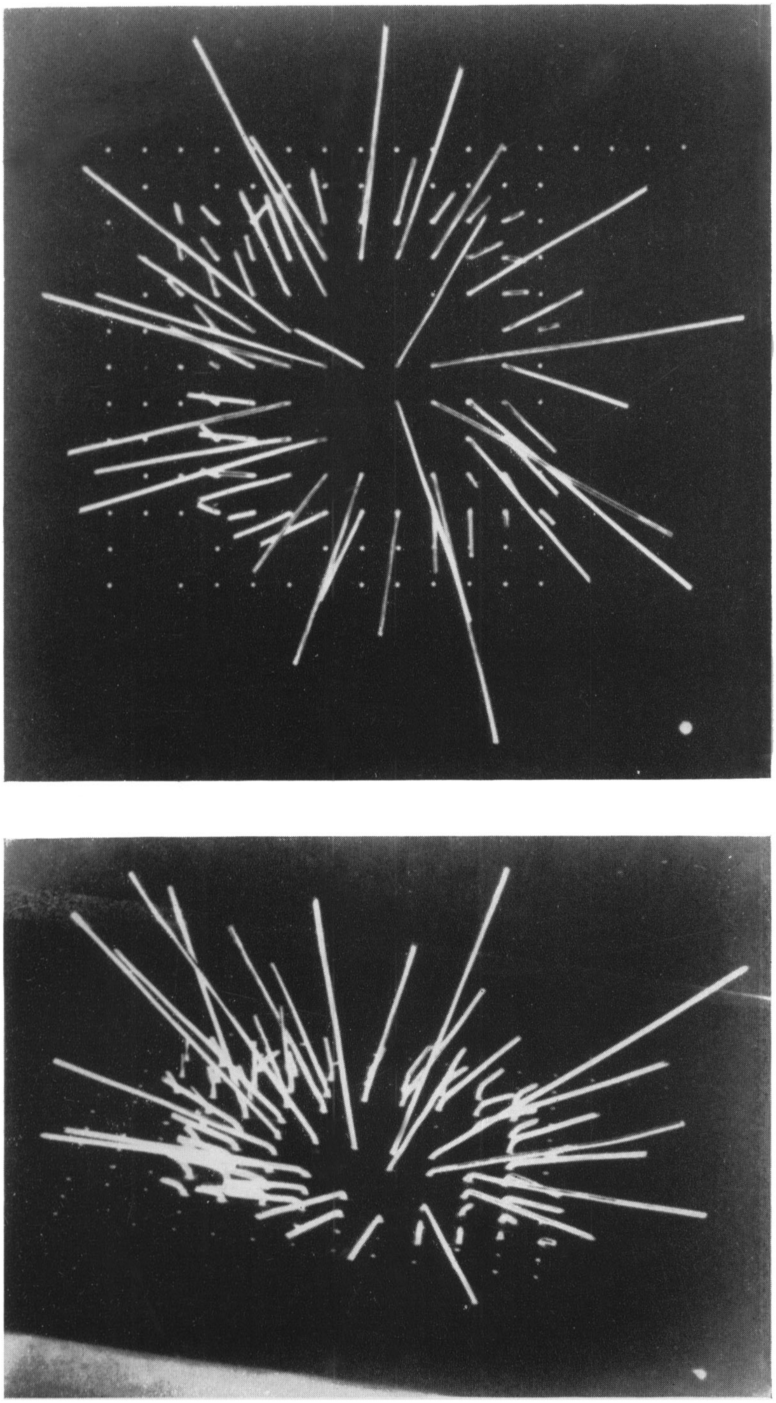

Fig. 15. Illustration of spatial distribution by means of a wire model.

sometimes observe crossed lines of force as if they were co-existing at the same point). These results about rotation can also be considered as direct observational evidence of twisted magnetic fields in active regions (**40**).

The next step forward we can make from the consideration of the *spatial* distribution of lines of force in sunspots as derived from observation. Figure 14 gives an academic idea about the

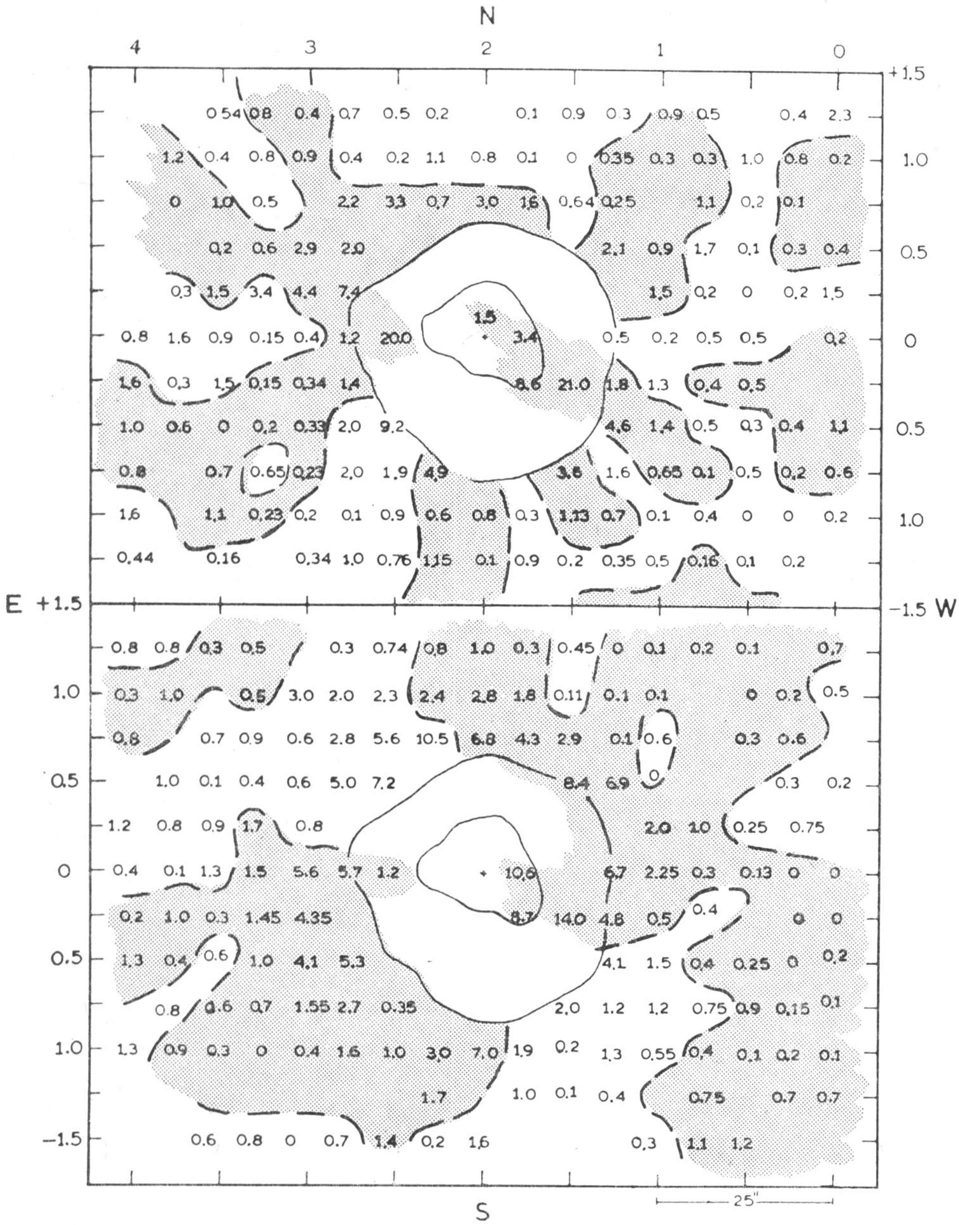

Fig. 16. The distribution of vertical currents (top) and vertical gradients (bottom) of the magnetic field inside a sunspot.

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pattern, and Figure 15 illustrates the same pattern in a more simple popular way with the aid of wire model. The most peculiar feature about this pattern is perhaps the *concentration of the field* in separate bundles or ropes directed more-or-less radially outwards. The field is mainly longitudinal inside the umbra and mainly transverse in the penumbra (41). Nishi in Japan (42) and Hénoux in France (43) have also come to the same conclusions. Sometimes a spiral-like

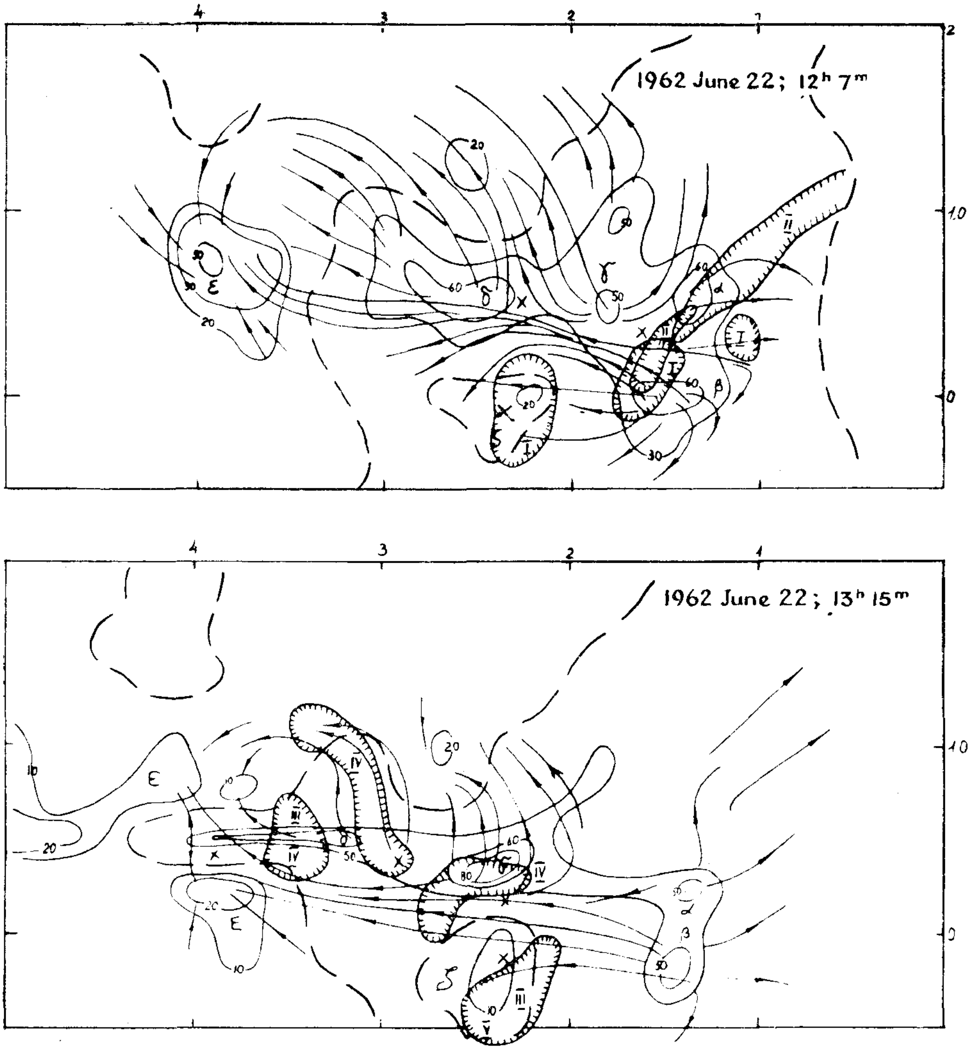

Fig. 17. The location of flares relatively to the magnetic fields, and the change in configuration of the magnetic field connected with a flare.

structure of the magnetic field is observed (Stepanov, Severny (44)) which follows very closely that of the Hα vortex structure around sunspots, as observed by Hale (Tsap (45)). The presence of a tangential component has recently also been noted by Adam (46).

A knowledge of the spatial pattern of the magnetic field allows us to determine the system of

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electric currents connected with sunspot, and the vertical field gradients according to Maxwell's fundamental equations

$$\operatorname{rot} H = \frac{4\pi}{c} j \quad ; \quad \operatorname{div} H = 0$$

The results of some calculations made by electronic computer are shown in Figure 16. The pattern of electric currents is most striking—it is similar to that we would observe if we looked at the coils of an electromotor along the rotating shaft. The origin of such structure is obvious—it is due to the ropes of lines of force directed radially outwards in which the field is mainly concentrated. The second point about these currents is again their fine structure—the contact of oppositely-directed currents as strong as 10^{11} amperes is not an exception, and is an immediate consequence of the very rapid rotation of the field vector.

The same figure shows that the regions of opposite vertical field-gradient are joining inside the sunspot, and this probably indicates that the lines of force are becoming more convergent in one part of the spot than in other parts, when the depth increases. This fact is additional evidence of the complex inhomogeneous structure of the magnetic fields inside sunspots (**47**).

The observations of Chevalier (**48**), Thiessen (**49**), and more recently by Bray and Loughead (**50**), showing the granular pattern inside sunspots are indicative of our attempts to understand the fine structure of magnetic fields. Although a magnetic field inhibits motions across the lines of force, convection inside sunspots can still exist, as was first suggested by Cowling (**51**) (we cannot, for instance, construct a correct model of a spot if we assume that convection is entirely inhibited). The interaction between the magnetic field and the convective current may presumably be responsible for the difference in the properties of the granules in the umbrae and photosphere (longer life-time of umbral granules etc.).

The coupling between magnetic fields and velocity-fields inside sunspots, as well as in the solar atmosphere in general, remains so far unexplainable—so difficult and obscure is the state of things here. As we have just seen in the umbra, where the magnetic field is almost entirely longitudinal, we observe the transverse component of motion (as Holmes (**52**) showed), and in the penumbra we observe that the inclination of the lines of force to the sunspot-axis is appreciably higher than the inclination of the almost-entirely surface radial outflow (Evershed motion). At the same time theory demands that the lines of force be rigidly connected with motion, and if we accept this the sunspot magnetic fields would be disintegrated in a very short time, incompatible with the observations. The way out of this contradiction may be to consider the spacing between the ropes or bundles of lines of force as slits or holes through which the gases can flow, because the field-motion coupling is not so strong there. If this is true, the electric currents described above could be closely connected with this system of streams.

Anybody who tries to consider the nature of a strong magnetic field from an observational standpoint can hardly avoid the impression of a very strange co-existence of controversial features, some of which are typical of the fields arising from the usual straight bar magnets (as Chapman first noted (**53**)) with no electric currents or potential fields, and others typical of those fields which are produced by a complex system of electric currents and, in particular, the most probable type of field, the so-called force-free fields where electric currents flow along the lines of force. The observed twisting, inhomogeneities and fine structure are apparently against potential fields; however, the run of field strengths and of inclinations of the lines of force with distance from a spot is in good agreement with that for a certain dipole, especially at great distances. Furthermore, if we remember that the magnetic field at the outer border of a spot is practically purely transversal, we should not there have vertical currents at all, if the sunspot field is force-free, but we observe quite appreciable vertical currents.

We again come to the same conclusion that a lot of observational, as well as theoretical, work should be done to produce a coherent pattern of solar magnetic fields in active regions.

5. DISTURBANCES OF THE SOLAR MAGNETIC FIELD

The deviations in the smooth run of magnetic lines of force such as twisting, rotation of the field vector etc. mentioned above, point probably to some instability or non-stationarity of

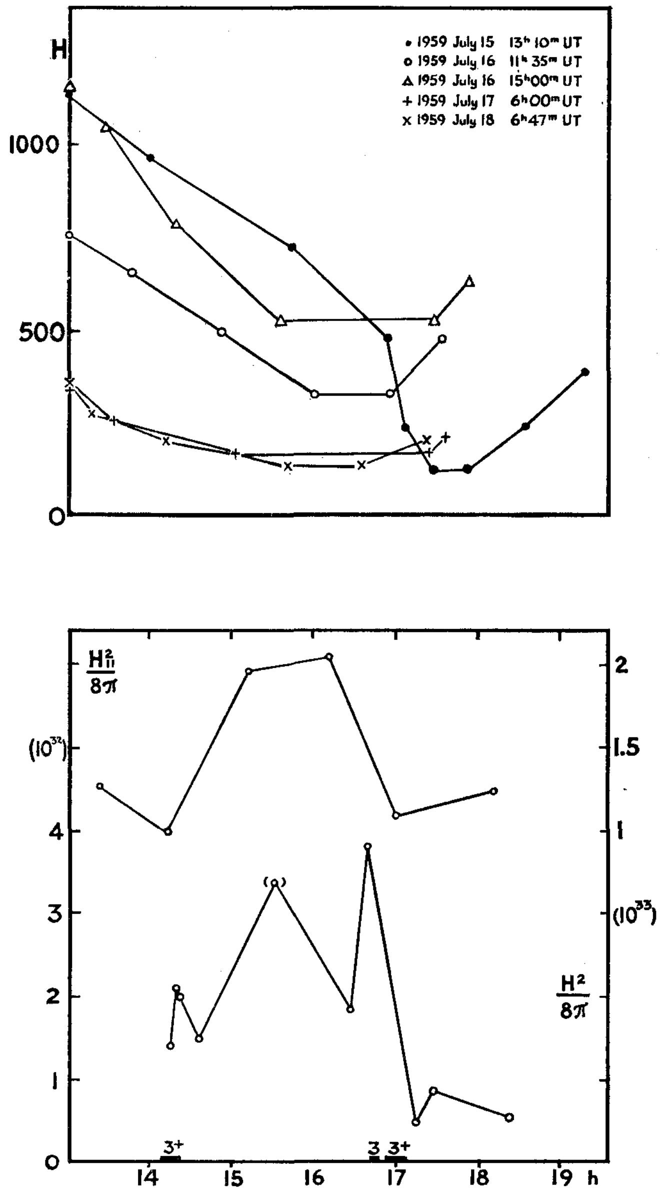

Fig. 18. The change of magnetic energy and field gradient associated with a great flare.

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plasma in the presence of a magnetic field. Usually such states are not those with the minimum of energy. Observations definitely show the appearance inside sunspot groups of highly non-stationary processes such as flares, moustaches, high-speed ejections and other similar explosion-like events. In Figure 17 is illustrated one of the many possible examples showing the location of flares relatively to the magnetic field. Flares on this combined map of magnetic fields appear in the actual places of contact of oppositely directed fields, and in the same figure we see how drastic are the changes in the magnetic fields connected with flares. Our examination, conducted over more than five years, of flares in connection with magnetic fields shows that they first appear at the places of peculiar behaviour of the magnetic field and, in particular, at the points which can be sometimes considered as neutral points (54) and sometimes as the points of bifurcation of the lines of force. These points, according to the theoretical considerations by Sweet (55), Dungey (56), Chapman and Kendall (57) and others (58), are the points of instability of the plasma.

The regions of peculiar behaviour of magnetic fields are usually, at the same time, those of strong rotation of the transverse field, and this is the reason why we can expect in these places the existence of strong vertical electric currents. Our recent observations confirm this conclusion.

The possibility of spasmodic changes of magnetic field were first suggested by Cowling (59). These changes are probably one of the most characteristic features of flare processes, as appears from numerous observations similar to that we have just seen. The most typical behaviour of the magnetic fields in connection with flares looks as follows. The magnetic fields before the flare are becoming more and more complicated and stronger, the horizontal gradients of the magnetic field are increasing and magnetic peaks are approaching. The fields are simplified, gradients become smaller, magnetic peaks and sometimes even sunspots are pushed away in connection with and soon after the flare (Severny (54), Gopasyuk (60), etc. (61)). Strong rotation of the transverse field vector is also observed during flares (36). Sometimes these changes are only temporary and the field pattern recovers to the initial state soon after the flare. Such cases were observed by Evans (62), Michard *et al.* (63), Chistyakov (64) and others. The late Professor Ellison revealed that the fine fibrile structure (repeating the pattern of the transverse field according to the Crimean observations (45)) is liable to sudden substantial changes during flares, but is restored again after the flare (65). Moreover, consideration of a number of sunspot groups without flares does not show such appreciable changes in the configuration and strength of the magnetic fields.

It is at least worth mentioning that quantitatively the measured change of magnetic energy associated with flares is comparable with the energy of the cosmic rays generated during the flare process [see Howard, Severny (67)]. It emphasises that conversion of magnetic energy into other forms of energy is probably the basic process in flares.

Figure 18 illustrates a quantitative example of such changes in the gradients and in the energies of the magnetic field connected with the great flare of 1959 July 16 according to (67).

6. CONCLUSION

I think that at this point I must stop further consideration of the subject, and summarize some general points relating to solar magnetic fields which follow from all that has been said above.

(*a*). Solar magnetic fields possess a fine structure; they are stronger and more concentrated in small areas than we have previously considered.

(*b*). Although for practical purposes we can use such ordinary concepts of magnetism as those of a dipole field or a force-free field etc., they are not adequate to explain observed solar

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magnetic fields. We should probably explore other possibilities within our present knowledge of magnetism to explain solar and stellar magnetic fields.

(*c*). The observed peculiarities in solar magnetic fields such as twisting, rotation of field, apparent crossing of lines of forces, neutral points etc., have probably close intrinsic relations to non-stationary processes on the Sun.

(*d*). Underlying the explosion-like processes on the Sun, such as flares, moustaches, ejections, etc., is probably the conversion of magnetic energy into other forms of energy; however, as yet we do not know what is the precise role of magnetic fields in these processes. Neither can we explain the observed rapid changes in the magnetic fields.

These notions are more intended to fix attention on the problems of further research, than to be definite conclusions. The nature of solar magnetic fields appears to be an extremely complicated problem and we can only be sorry that those times are passed when Eddington used to say "there are nothing more simple than stars."

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