ON THE DEVELOPMENT OF MAGNETIC FIELDS IN ACTIVE REGIONS

M. K. V. BAPPU
Kodaikanal Observatory, India,

V. M. GRIGORJEV and V. E. STEPANOV
Sayan Observatory, Sib. IZMIR., U.S.S.R.

(Received 29 February, 1968)

Abstract. Transverse and longitudinal magnetic field scans together with K_{232} spectroheliograms that cover the early phases of active region formation reveal the following:

(a) The new active region forms near the periphery of an old magnetic region. There is evidence that the new region forms an interrelated system with the old magnetic structures on the sun.

(b) Noticeable changes in the background magnetic field are seen nearly 3 days prior to the appearance of the sunspot. Magnetic hills of the longitudinal component appear along with bright localized K_{232} emission. Subsequently the K_{232} emission spreads along the boundary of one or two adjacent supergranules and at the time of sunspot formation occupies the whole supergranular cell.

(c) Transverse fields with strengths of 100–150 gauss form closed regions in the area of the longitudinal component hills, in the very early phases of the region. These fields stretch and link up the two areas later, at which time the peak transverse fields with values near 250 gauss coincide with the zero line of the longitudinal field. When subsequently the spots appear in the new region, the transverse fields are located about the hills of the longitudinal field. The total field vectors just prior to sunspot formation are pressed to the surface. These are inclined about 45° to the surface after the spot appears. The findings indicate that the magnetic field of a new region emerges from the sub-photospheric layers. It is highly likely that the dynamics of a supergranule influences only the emergence of the magnetic field into the upper layers of the solar atmosphere.

1. Introduction

The investigation of changes of the patterns of magnetic field and radial velocities as well as granular and supergranular structures in a region, prior to sunspot formation, is likely to yield much valuable information towards the understanding of the origin of the sunspot mechanism.

Information available today on the behaviour of the magnetic fields at the moment of sunspot formation is scanty. It is known that sunspots are formed in bipolar magnetic regions having a field strength of 2 gauss or greater. Simultaneously the brightness of the chromospheric network is enhanced. As Butler (1922, 1924), has shown, the formation of a new area of calcium flocculi is a more rapid process than its disappearance. Bumba and Howard have shown recently (1965a, b) that a new bipolar magnetic field always occurs either in the region of an old field or in its close vicinity. In a majority of cases the growth of the magnetic field as well as of the calcium flocculi is from the following part to the leading one.

The magnetic field in the photospheric level is seen to exist 2–3 days before the sunspot group formation and has a completely multipolar structure. There is a flux imbalance between those of opposite polarity. Gopasyuk has recently studied the magnetic fields at the time of sunspot formation in the active region, when the leader had already formed. He noticed that such development was accompanied by the enhancement of field strength at the hill centre with some field compression at its periphery.

We know little at present of the changes in the structure of the transverse magnetic fields in a region during sunspot formation.

SIMON and LEIGHTON (1964) have shown the existence of a large-scale cell system of tangential velocities over the whole solar surface, termed the 'supergranules'. The boundaries of the supergranules coincide spatially with the network of weak magnetic fields in the photosphere, the chromospheric network seen in the K line of Ca^+, and the network of downward-flowing matter seen in Hα and Hβ. The dynamics of supergranulation perhaps play an important role in the formation and development of sunspots. The first bright emission of the chromospheric network in the K line appears at the crossings of adjacent supergranules. Subsequently the emission extends around the supergranule and covers the whole of it. The sunspot also appears at the border of the neighbouring supergranules and in its future development may cover one or more supergranules.

Very little is also known of photospheric and chromospheric velocities in the line of sight in a region during sunspot formation. VASILJEVA (1961) has observed a sudden increase of velocity in a magnetic hill region of 100 gauss, wherein 3 days later some sunspots were formed. GOPASYUK (1967) has also shown that large-scale motions of descent are observed in both chromosphere and photosphere in a region during sunspot formation. The highest velocity of descent is observed in the magnetic-field region of the appearing spot. BUMBA (1967) has also observed a similar phenomenon in pores and young spots.

The changes in granular structure accompanying spot or pore formation and development were shown by BRAY and LOUGHHEAD (1964). At the moment of a new pore formation a large number of dark lanes appear that seem to be darker than the ordinary intergranular spaces. Bright granules between these lanes are oriented along directions parallel to these lanes. VASILJEVA (1968) has observed that even 2 days before sunspot formation the granular elements are stretched with an accompanying increase in brightness, several percent above the normal values of the quiet photosphere.

We report herein the results of a study of longitudinal and transverse magnetic fields in a region prior to and during sunspot formation.

2. The Observations

Our primary interest was to study the magnetic-field characteristics in the very early stages of development of an active region. For this purpose we chose the active zone in the latitude range $+10° \leqslant \phi \leqslant +30°$ which had a high probability for the occurrence of a new active region. This latitude belt, if weather conditions permitted, was scanned each day from May 1 to May 16, 1966, by means of the Sayan Observatory magneto-

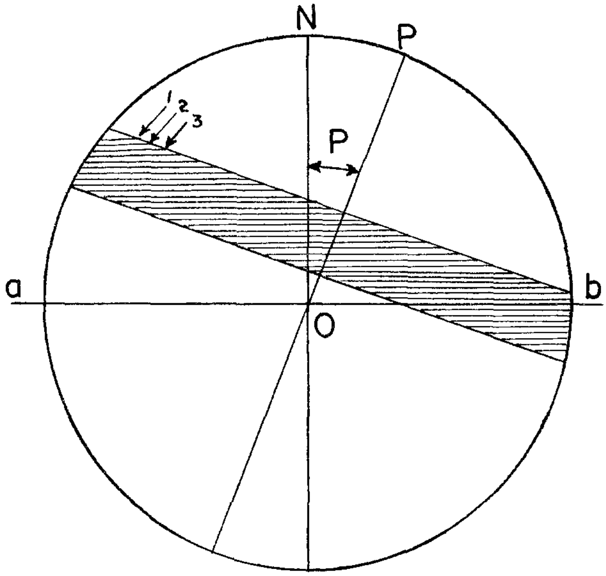

Fig. 1. Scans of the studied region, a, b = direction of the daily parallel, ON = direction of the celestial North, OP = position of the axis of the sun's rotation.

graph (KUZNETSOV *et al.*, 1966) with a resolution of $18'' \times 1.8''$, and using the Fe I 5250 Å line. The solar image was scanned across the slit along the daily parallel at the rate of 2″/sec. The time constant of the magnetograph was 5 sec. Successive scanning of the studied region was done according to the scheme shown in Figure 1, along parallels separated by 20″. The exact coordinates of a location on the slit at any instant can be read off from the image position in an auxiliary guider synchronized with the primary image.

During the period of this study, four new groups were formed. We report here on the development of magnetic fields associated with sunspot group N55 as presented in the Bulletin *Solar Data*. The reduction of the magnetic data was carried out with an electronic computer. The relationship between the magnetic fields measured and the supergranular structure of the calcium network was studied with the aid of K_{232} spectroheliograms obtained at the Kodaikanal Observatory.

3. General Description of the Development of the Magnetic Field during the Appearance of a Sunspot Group

We show, in Figure 2, the charts of the observed longitudinal magnetic fields on 4 days that cover the formation of the sunspot group. It will be seen that the new active region formed at the border of an old bipolar magnetic region in which two rotations previously a large sunspot group was observed. Our maps of May 9 show that the old bipolar magnetic region was on that day close to the East solar limb. The region to the

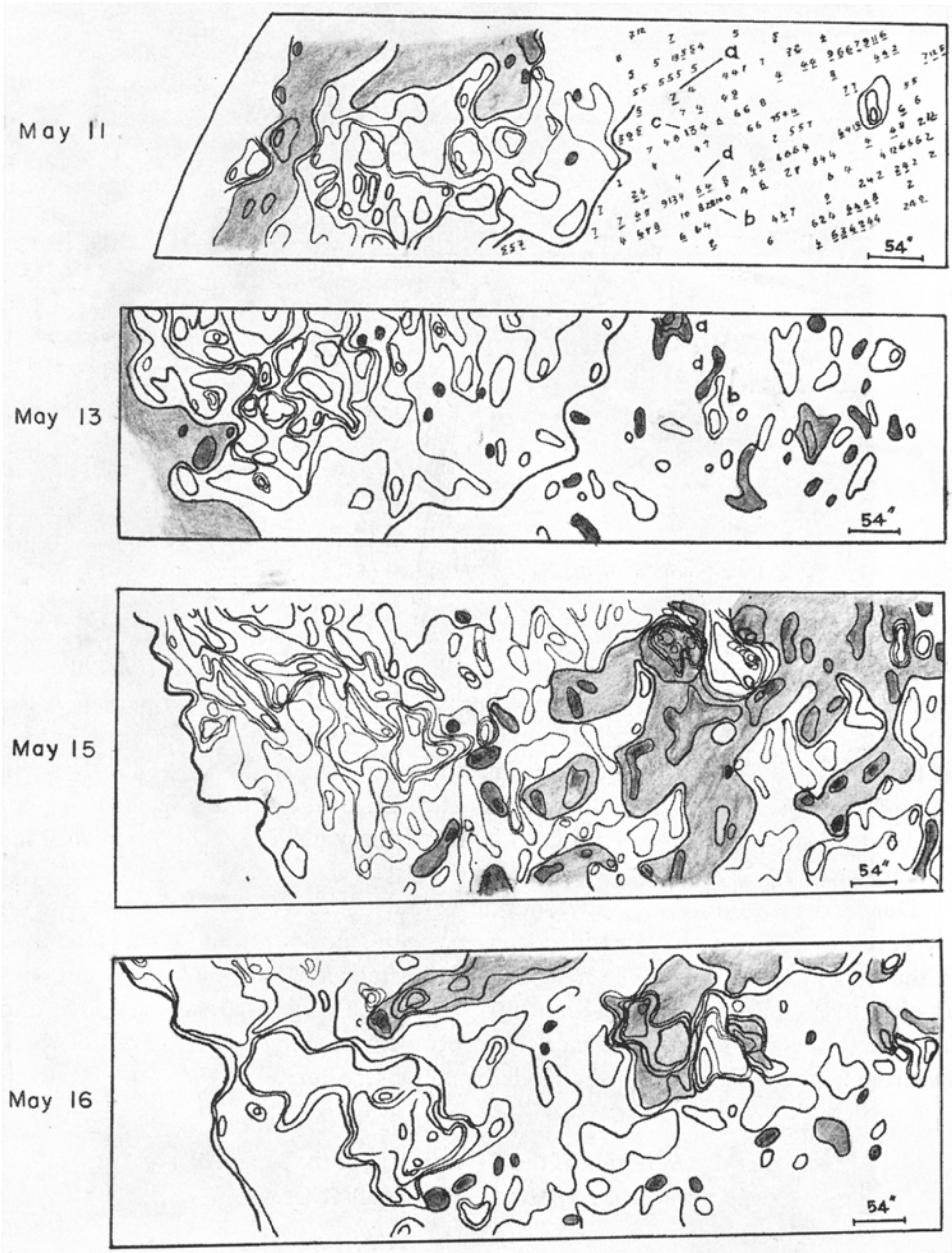

Fig. 2. Charts of the longitudinal magnetic-field component. Isogausses correspond to the field strengths 5, 15, 20, 50 gauss and > 50 gauss, respectively. Shaded areas are N polarity. A bold full line is the zero line of the field $H_{\|} = 0$.

West of it is occupied by a weak background field, mostly of Southern polarity.

On May 11, there appeared on the border of the leading part of the old bipolar region a small hill of Northern polarity with a field strength of 7 gauss. This hill is marked *a* in Figure 2. A field of Southern polarity with the maximum strength of 13 gauss existed in the hill *c* to the south of *a*. To the Southwest of *a*, a magnetic hill *b* of Southern polarity is observed in which region subsequently the leading spot of the group seems to have developed. Close to it a weak field of opposite polarity is present.

On May 13 we notice an appreciable change in the longitudinal field structure. The field strength in the hill *a* increased to 26 gauss. There is also an increase in extent of this hill. The neighbouring hill *c* of South polarity has disappeared. The configurations *b* and *d* experienced minor changes of shape with almost no appreciable change in field strength.

On May 14, in the region of the hill *a* the following spot of the developing spot group appeared. The hill *d* of Southern polarity appeared to have moved in very close to the North polarity region. The magnetic fields of both polarities exceed 200 gauss. The regions with the strong field are very compact. Also, the region of North polarity is surrounded on all sides by South polarity fields. The boundary of the old bipolar magnetic region does not experience any marked changes.

The leading spot of the newly developing group appeared in the hill of Southern polarity on May 15. If on May 14, the hill of North polarity was found to be surrounded by the South polarity field, the picture on May 15 is just the opposite. The South polarity field now occupies a compact region surrounded by North polarity fields ranging from 5 to 25 gauss. The latter field covers a very great area and projects far into the leading part of South polarity of the old bipolar region.

By May 16, the spot group has developed completely. The region occupied by the field of North polarity has changed considerably. The area of this field has decreased and the bays caused by the projections into the area of Southern polarity have also disappeared. The field of South polarity occupies the region to the South and Southeast with respect to the leading spot, and it is now impossible to draw a boundary between the field of the old bipolar region and the field of South polarity of the new active region.

The magnetic field in the photosphere thus appears 3 days prior to sunspot formation and has a complex multipolar structure. Close by the magnetic hill, in which region some spots appear later, we see fields of opposite polarity. The new active region develops in the direction from the following part to the leading one.

4. Magnetic Fluxes in the Developing Region

We present, in Table I, the values of the fluxes of North and South polarity of the new active region. The last column gives the difference between the two values on each day.

On May 11, when only small magnetic-field hills of both polarities exist and when the first brightening of the calcium network appears, the total magnetic flux equals 0.1×10^{21} maxwells and has a Southern polarity. On May 13 the net flux has the same

TABLE I

Date	ϕ_S(mx)	ϕ_N(mx)	$\Delta\phi = \phi_S - \phi_N$
1966 May 11	0.2×10^{21}	0.1×10^{21}	0.1×10^{21}
13	0.2×10^{21}	0.3×10^{21}	0.1×10^{21}
14	1.1×10^{21}	–	–
15	1.2×10^{21}	1.4×10^{21}	0.2×10^{21}
16	2.2×10^{21}	3.1×10^{21}	0.9×10^{21}

value but with a Northern polarity. This flux value increases slowly to 0.2×10^{21} mx until May 15. It increases sharply to 0.9×10^{21} mx on May 16, when a well-developed sunspot group is observed. The flux values for May 14 are not given because weather conditions prevented the securing of complete magnetic field scans that day.

We note that during the formation and development of a new active region, an imbalance of the magnetic fluxes is observed.

5. The Magnetic Link with an Old Bipolar Magnetic Region

The mean magnetic-field strength values of the longitudinal fields in the old bipolar region can be seen in Table II. In the period May 11–15, no noticeable change is seen in the mean field strength of the region. However, on May 16, when the excess magnetic flux of North polarity of the new region extends into the leading part of South polarity of the old bipolar region, we notice an enhancement of the mean field strength.

TABLE II

Date	$H_{\parallel}$ (gauss)
1966 May 9	16
11	13
13	15
14	13
15	14
16	22

The synchronous change in the resulting magnetic flux of the new region and in the mean strength of the leading part of South polarity in the old bipolar region, permits us to reach the conclusion that there exists a magnetic link between the old magnetic fields and those forming in a new region. The excess magnetic flux of North polarity in the new active region must be partially closed on the leading part of the old bipolar region. This is verified by the charts in Figure 3, where the approximate picture of direction of the field force lines is shown in projection on the tangent plane. Some of these force lines extending from the region of the field of North polarity cross the zero line of longitudinal field that separates the old and new regions and close within the field of South polarity. The new region is thus not an isolated object in the magnetic domain but one that possesses a certain relationship

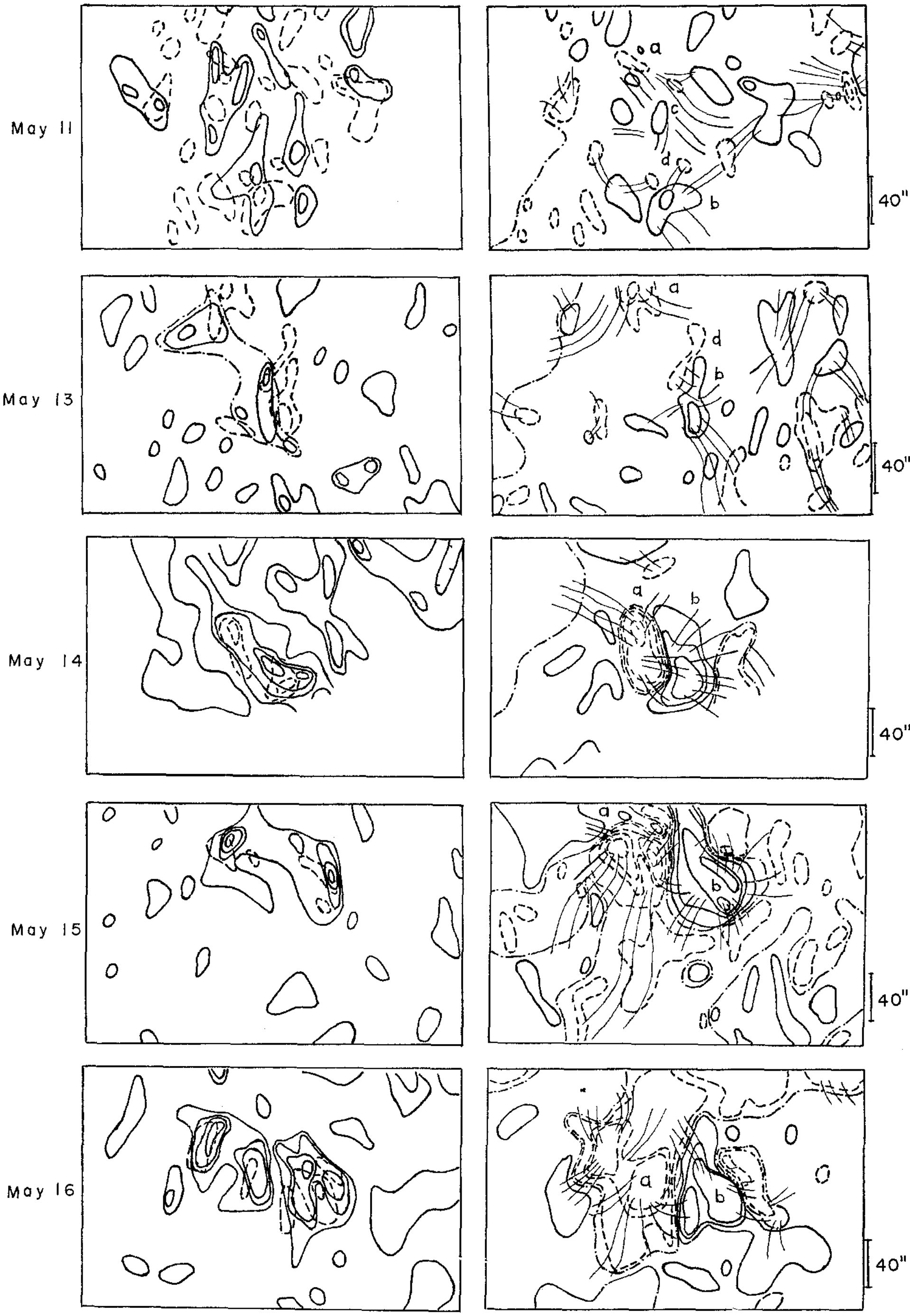

Fig. 3. Left: the charts of the magnetic-field transverse component. Full lines: isogausses every 50 gauss, starting with 100 gauss; dotted lines: hills of the longitudinal magnetic fields. – Right: the charts of the longitudinal component and approximate picture of the force-line direction of the magnetic field in projection on the tangent plane. Full lines: isogausses of S polarity; dotted lines: N polarity.

with the magnetic fields of the neighbouring bipolar or unipolar region. This was pointed out already by ALEKSANDROVICH and STEPANOV (1968). The interrelation of different magnetic-field structures is illustrated by many other well-known phenomena such as the presence of magnetic field hills which are 'prominence attraction centres' (STEPANOV, 1958), activization of prominences and filaments (BRUZEK, 1951, 1952; SMITH and BOOTON, 1962; MORETON and RAMSAY, 1963) during flares, the occurrence of mirror reflection 'ghosts' of the unipolar magnetic fields in the opposite hemisphere (BUMBA and HOWARD, 1965b) and the presence of sympathetic flares (RICHARDSON, 1951).

6. The Structure of the Transverse Magnetic Field

The full lines in the left half of Figure 3 depict the spatial aspects of the transverse magnetic fields. The dotted lines indicate the longitudinal component.

On May 11, the transverse fields with strengths of 100–150 gauss form two closed regions in an area of hills of the longitudinal component, of opposite polarity. It is in these hills that the main sunspot group developed later. We see here that the locations of maximum transverse fields do not coincide with the hills of the longitudinal field. On May 13, we notice that the 100 gauss contour of the transverse field stretches in a way so as to link up the two main hills of opposite polarity of the longitudinal field. This stretched configuration is maintained on May 14, and we observe in addition that the longitudinal component hills are now within the 150 gauss outline of the transverse field. The maximum transverse fields of strength 250 gauss are on the zero line of the longitudinal field. The force lines of the magnetic field show that the transverse field connects the regions of opposite polarity. We find this displayed very distinctly on May 14. The leading sunspot is formed the next day, by which time the transverse fields have changed their structure greatly. Strong transverse fields are now located near the hills of the longitudinal field. These transverse fields decrease to values around 75–100 gauss on the zero line of the longitudinal field.

On May 16 a well-developed sunspot group is seen and the transverse fields form two closed regions around the hills of longitudinal field of opposite polarity. The contour that depicts the maximum longitudinal field in the leader spot is surrounded on all sides by transverse fields of strength 200 gauss or greater. Such a structure is characteristic of a developed sunspot (STEPANOV and GOPASYUK, 1962). The strength of the transverse field at the zero line has decreased to 60 gauss. We have evaluated the relation between the average transverse field $H_\perp$ and the longitudinal one $H_\parallel$ over the period of development of the sunspot group. These results are given in Table III. On May 11 and 13, when the leader spot had not yet appeared, the transverse fields exceed the longitudinal ones by a factor of 20. With the appearance of the following spot this ratio of $H_\perp/H_\parallel$ decreased to 8. After the leader's appearance and the further development of the sunspot group this relation decreased to 4.

We depict in Figure 4 the direction and total field vector on the axis of the sunspot group. On May 14 the magnetic field is strongly pressed to the surface. On May 15, after the appearance of the following and leader spots the field vectors incline upwards.

TABLE III

Date	$H_{\parallel}$ (gauss)	$H_{\perp}$ (gauss)	$\frac{H_{\perp}}{H_{\parallel}}$
1966 May 11	2.7	54	20
13	2.4	51	20
14	9.8	77	8
15	14.1	71	5
16	17.4	67	<4

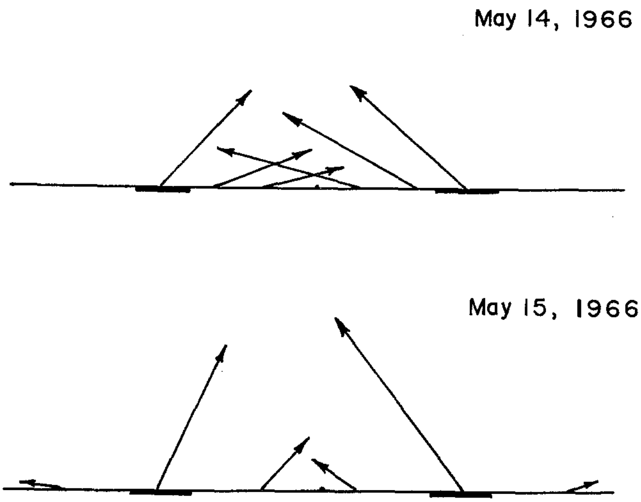

Fig. 4. Schematic pictures of the total field vector of a magnetic field at the sunspot group axis.

The angles of these vectors with the solar surface are in the neighbourhood of 45°. The strength of the total vector in the region of the zero line is greatly reduced.

We conclude then that (a) the stretching of the transverse field isogauss contours in a direction so as to connect the hills of the longitudinal field wherein sunspots appear later, (b) the presence of a strong transverse component reaching maximum values in the region of the longitudinal-field zero region, prior to the appearance of a sunspot, (c) the appearance of one spot of the group and the immediate reduction of the transverse values along the zero lines with an augmentation of the field values around the hills of the longitudinal field, favour the concept (PARKER, 1955; KUKLIN and STEPANOV, 1963; VITINSKIJI and IZSANOV, 1964; GOPASYUK, 1966) that the magnetic field of a new active region emerges from the sub-photosphere layers. The force lines are essentially parallel to the surface just before the birth of a spot. An adjustment in orientation of the force lines takes place subsequently after spot formation.

Support for this conjecture can be had from a study of white-light granulation. BRAY and LOUGHHEAD (1964) point out that the appearance of dark lanes of the intergranular background along which bright granules are oriented during the formation of a new pore, suggests that the magnetic-force lines come out of the sub-photospheric layers. VASILJEVA (1968) finds evidence using correlation techniques that the bright granular elements, in a longitude of subsequent sunspot birth, even experience a stretching. This feature is noticed even 2 days prior to the appearance of the sunspot.

7. The Structure of the Longitudinal Field and its Relationship to the K_{232} Chromospheric Network

We now examine the relationship between the K_{232} network and the spatial distribution of the magnetic field. A superposition of the outlines of the calcium network onto the charts of magnetic field could be done with ease since the coordinates of the scanned region were known. Figure 5 shows for each day the outlines of the network and the magnetic-field distribution for the region. We note that the longitudinal component assumes high values at the boundaries of cells of the chromospheric network, which according to SIMON and LEIGHTON (1964) coincides with the network of supergranulation. The field strengths at the supergranule boundaries reach 25 gauss. There is also the tendency to encounter opposite polarities at near opposite sides of the supergranule boundary.

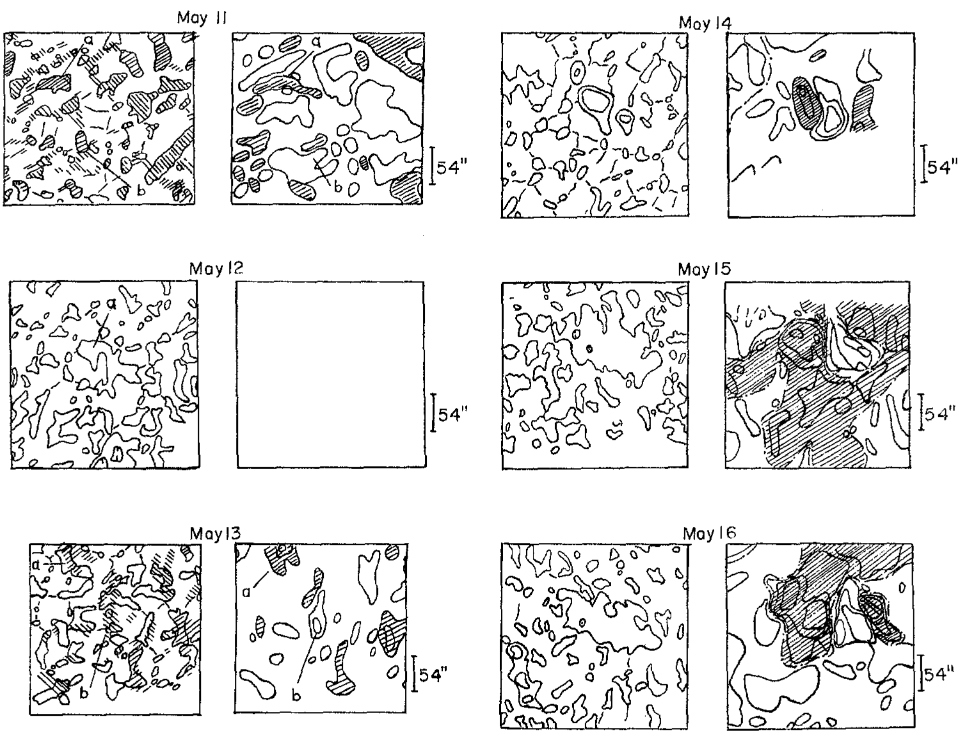

Fig. 5. Left: calcium pattern from the spectroheliogram. The regions of N polarity are shaded with inclination to the right, and those of S polarity with inclination to the left. – Right: the charts of the longitudinal field component. The shaded regions are regions of N polarity.

Simultaneous with the formation of hill *a* of the longitudinal component of North polarity on May 11, a small calcium flocculus in the chromosphere appeared at the boundary of the supergranulation cell. On either side, two very localized magnetic condensations of opposite polarity can be seen. At the other end of the supergranulation cell one sees a hill of South polarity. This hill is also at the cell boundary of the chromospheric network. Two small regions of North polarity adjoin it on the Northern and Southern sides. We have no magnetic field scans on May 12. However, the calcium spectroheliograms show that emission from the region *a* spreads to the neighbouring cell.

On May 13, the magnetic field in the hill *a* and the calcium flocculus located on the Eastern boundary of the supergranule cell have both increased in intensity. The strength of the field in the Southern region of the neighbouring cell has also increased, while the calcium emission has intensified along the whole cell boundary. The greatest brightness of flocculi and the strongest field are on the Eastern boundary of the supergranule.

Simultaneous with the formation of the following sunspot in the region *a* the calcium emission fills the whole supergranular cell. The flocculus area reached 6×10^{18} km^2, which is of the order of the supergranular area. The hill in the magnetic field of Southern polarity, which on May 13 is on the Eastern supergranular boundary, moves to the North along it. A considerable intensification of the longitudinal component of magnetic field is noticed. At the same time, on May 15 and 16, the flocculus intensifies in brightness with a corresponding increase in area.

We note that the availability of sufficiently good resolution in magnetic scanning allows us to observe a complex magnetic-field structure on the supergranular scale. The hills of longitudinal magnetic fields are located on the boundaries of supergranulation cells. The opposite sides of a supergranular cell may have fields of different polarity. We also see that in any localized region of intense calcium emission, longitudinal magnetic fields of opposite polarity can be encountered.

The transverse magnetic fields, as can be seen from a comparison of Figures 3 and 5, lie within the supergranule or cover it entirely. Since our measures of the transverse component are reliable only for field strengths in excess of 80 gauss, it is not possible for us to study in detail the structure of the transverse field within the scale of the supergranules. However, the hills of the transverse component with strengths greater than 100 gauss either get within the supergranule or cover the whole of it.

The strongest transverse fields cover the cells of chromospheric network, on the boundaries of which we have observed the formation of the hills of longitudinal fields during the development of the sunspot group. These longitudinal field hills in the course of development of the spot group are seen to migrate along the supergranular cell boundary. The sunspot does not necessarily appear where the magnetic-field hill and the first brightening of K_{232} took place.

The investigations of Bumba, Howard, Leighton and Simon have indicated the very important role of supergranulation dynamics during the process of formation and development of sunspots. As we have shown in a preceding section the magnetic field of a new active region comes out of the sub-photospheric layers and forms some interrelated system with other magnetic structures on the sun. We may, therefore, conclude that it is highly likely that supergranulation dynamics influences only the emergence of the magnetic field into the upper layers of the solar atmosphere. It is obvious that further investigation of the high-resolution structure of the magnetic field during sunspot appearance is necessary, particularly the transverse component, before we can confirm such a conjecture.

8. Conclusions

We summarize below our principal findings in this study.

(1) The new active region described above has been formed in the weak background field of South polarity at the boundary, in the vicinity of the leading part of an old bipolar magnetic region.

(2) A noticeable change in the background magnetic field is seen 3 days before the appearance of the sunspot. At this time a magnetic hill with a field strength two or three times greater than that of the background field appears.

(3) Simultaneous with the appearance of the hill of the longitudinal component the bright localized regions of the K_{232} network are formed. In the subsequent days the K_{232} emission intensifies and in the form of bright filaments spreads along the boundary of one or two adjacent supergranules. At the time of sunspot formation the calcium flocculus occupies the whole supergranular cell.

(4) During the entire early stage of the development of the active region a balance of magnetic field is observed.

(5) The new active region is not an isolated feature but forms a certain interrelated system with the old magnetic structures on the sun.

(6) The transverse magnetic fields during sunspot appearance form a structure that stretches in the direction connecting the hills of longitudinal fields where later some sunspots have formed. Prior to sunspot formation strong transverse fields are observed on the zero line of the longitudinal field pattern. These transverse fields attain maximum values during the appearance of one sunspot. They decrease in strength subsequently and are located around the hills of the longitudinal field when the group is well developed. The direction of the total field vector on the group axis during the first days of its development shows that the magnetic field is strongly pressed to the surface.

(7) The development of the active region takes place in the direction from the following part to the leading one.

(8) The longitudinal magnetic fields in the scale of the supergranules have a complex structure. On one and the same supergranule the field may have opposite polarities at opposite sides of the cell or even in a localized condensation of K_{232} emission at the cell boundary.

(9) The transverse magnetic fields lie within the cell of supergranulation or cover the whole of it.

(10) During the development of the new active region, the hills of longitudinal field are seen to shift along the boundary of the supergranule. The sunspot does not necessarily appear at the first location of the longitudinal hill or the first position of brightening of the calcium network.

References

Aleksandrovich, I. I. and Stepanov, V. E.: 1968, *Izv. Sib. IZMIR* (in press).

Bray, R. J. and Loughhead, R. E.: 1964, *Sunspots*, Vol. VII (International Astrophysics Series), Chapman and Hall, London, p. 67.

Bruzek, A.: 1951, *Z. Astrophys.* **28,** 277.

Bruzek, A.: 1952, *Z. Astrophys.* **31,** 99.

Bumba, V.: 1967, *Izv. Krym. astrofiz. Obs.* **36,** 56.

Bumba, V. and Howard, R., 1965a: *Astrophys. J.* **141,** 1502.

Bumba, V. and Howard, R.: 1965b, *Astrophys. J.* **141,** 1942.

Butler, C. P.: 1922, *Mon. Not. R. astr. Soc.* **82,** 334.

Butler, C. P.: 1924, *Mon. Not. R. astr. Soc.* **84,** 134.

Gopasyuk, S. I.: 1966, *Izv. Krym. astrofiz. Obs.* **35,** 139.

Gopasyuk, S. I.: 1967, *Izv. Krym. astrofiz. Obs.* **36,** 56.

Kuklin, G. V. and Stepanov, V. E.: 1963, *Soln. Dann. Bjull.* **N2,** 43.

Kuznetsov, D. A., Kuklin, G. V., and Stepanov, V. E.: 1966, *Nauka* **1,** 133.

Moreton, G. E. and Ramsay, H. E.: 1963, *Publ. astr. Soc. Pacific* **72,** 357.

Parker, E. N.: 1955, *Astrophys. J.* **121,** 491.

Richardson, R. S.: 1951, *Astrophys. J.* **114,** 356.

Simon, G. W. and Leighton, R. B.: 1964, *Astrophys. J.* **140,** 1120.

Smith, H. J. and Booton, W. D., 1962, *Geophys. Res. Notes* No. 58.

Stepanov, V. E.: 1958, *Izv. Krym. astrofiz. Obs.* **20,** 52.

Vasiljeva, G. J.: 1961, *Soln. Dann. Bjull.* **N12,** 64.

Vasiljeva, G. J.: 1968, *Bull. Pulkovo Obs.* (in press).

Vitinskiji, U. I. and Izsanov, R. N.: 1964, *Soln. Dann. Bjull.* **N10,** 57.