Part I

GENERAL DEVELOPMENT OF AN ACTIVE REGION

PATTERNS OF ACTIVE REGION MAGNETIC FIELD DEVELOPMENT*

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ABSTRACT

We discuss some characteristics of the appearance and development of magnetic fields within active regions as well as the large-scale ordering of activity into complexes of activity. It is not possible to separate a study of the evolution of active regions from a study of the model of the activity cycle. Many of the results obtained in the last few years concerning the development of active regions and large-scale activity have not been easily explained within any of the solar activity models. A chronological scheme of the development of a 'typical' C- or D-type active region is presented. We point out that the appearance of magnetic flux at the solar surface seems always to be a relatively rapid event, occurring during the course of a day or so. If the region does not receive more magnetic flux to make it a large region or if there is not a resurgence of activity later in its lifetime, the rest of the development is a gradual expansion and mixing of magnetic flux with the surrounding background field pattern.

1. The Magnetic Cycle

A theoretical model of the birth and development of an active region cannot be constructed without an understanding of the physical mechanisms involved in the solar cycle. We cannot separate the study of the solar cycle from the study of the development of active regions. In recent years there have been only a few models of the solar activity cycle suggested. The enormous complexity of the problem has so far made it impossible to construct a rigorous theory of the activity cycle. The models suggested have been phenomenological models which help us to visualize a possible solution.

Parker (1955) suggested a model which supposed toroidal magnetic fields – part of a dynamo wave – which move toward the equator under the solar surface. Magnetic buoyancy brings loops of these magnetic-flux ropes to the surface to form active regions. The equatorward drift of these magnetic fields provides the latitude drift of Spoerer's law. This model gives an explanation of some of the phenomena of solar activity, but it is not as complete in its description of the phenomena as is Babcock's model. Moreover, the recent observations of the latitude drift of aging active region

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** On leave from the Mount Wilson and Palomar Observatories.

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magnetic fields – especially the different behavior of the leading and following polarities – does not fit this model well.

Babcock (1961) proposed a model which starts with an initial bipolar field which in low latitudes consists of subsurface flux tubes. Differential rotation draws these flux tubes out and twists them until, first at high latitudes, magnetic buoyancy brings loops of lines of force to the surface. The active latitudes move to the equator as the cycle progresses. As the old regions expand and their magnetic fields weaken, the following polarity fields drift preferentially to the pole and the leading polarity fields drift to the equator and merge with those from the opposite hemisphere. Thus the polar fields reverse polarity and the stage is set for the next half of the 22-year cycle.

Although Babcock's model is the most successful one suggested so far, it cannot explain all the observed phenomena. One observation seems to us to be particularly difficult to explain. During the first few months of the present cycle, the first new cycle regions were forming in one broad longitude zone, in an area where weak fields from the old cycle were still visible and presumably were moving toward the polar

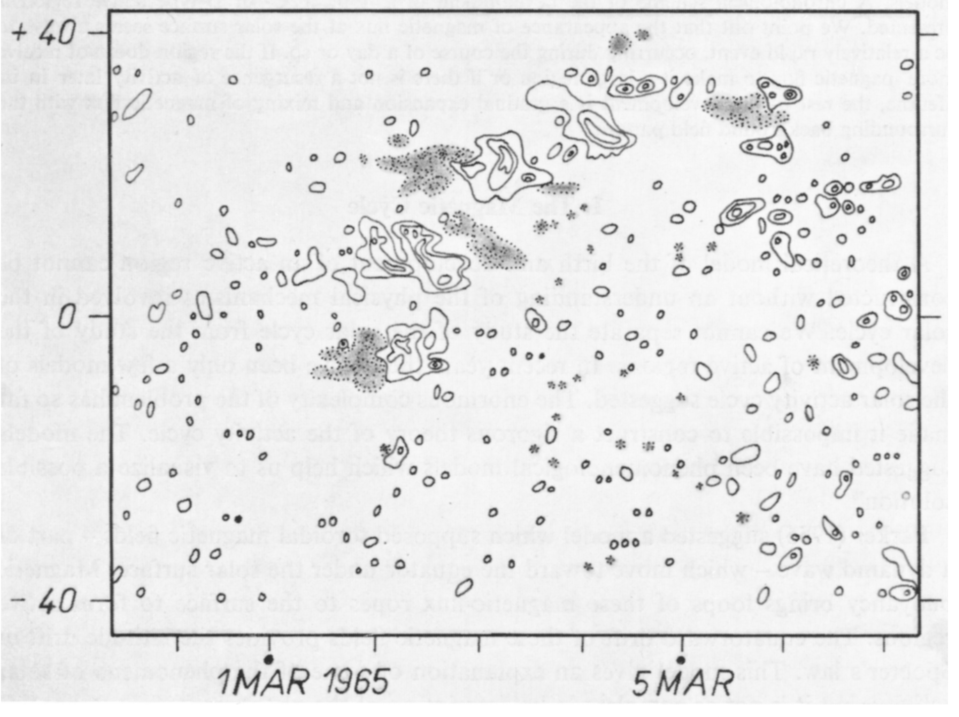

Fig. 1. *A portion of the magnetic-field synoptic chart for rotation no. 1491. East is to the right. Positive magnetic polarity is indicated by solid lines, and negative polarity by dotted lines and shading. The gauss levels are 6, 12, and 20 gauss. The new-cycle regions in the North have negative magnetic fields in their leading portions.*

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regions. An example of this is shown in Figure 1. It is difficult to visualize how this can happen in Babcock's model.

Recent results concerning the development of active region magnetic fields (Bumba and Howard, 1965*a*) have added to our knowledge of the phenomena, but so far these results and others have not added to our understanding of the activity-cycle model. From the observations we cannot at this time see direct evidence that an active region forms as a result of the emergence to the surface of a tube of magnetic lines of force.

2. Large-Scale Activity

Recent results suggesting the large-scale ordering of activity (Bumba and Howard, 1965*b*; Warwick, 1965; Švestka, 1967) have not found an explanation in any of the models suggested so far.

A complex of activity (see Figure 2) is the grouping together in one large longitude zone of a number of active regions. When the level of activity is sufficiently low, the appearance of the active region within the complex may be seen to follow a characteristic pattern. The active regions during the first few rotations are large and concentrated near the center of the complex. In subsequent rotations the boundaries of the complex expand, and the active regions which form are smaller. The expanding fields of the old active regions may fill a very large area in both hemispheres. A unipolar magnetic region (seen with 23 arc-sec resolution) may form at high latitudes. At lower latitudes large-scale fields can be seen which appear to extend into interplanetary space.

A complex of activity is intermediate in importance between a single active region and the activity cycle itself, and it shows some of the characteristics of both. For example, the development of its activity is rapid compared to its decay, and its area grows steadily at first then decreases irregularly.

3. The Birth and Development of an Active Region

We present some characteristics of the birth and later development of an active region which have been noted so far. These concern principally the magnetic fields and the calcium plages. The results are a combination of earlier work (Bumba and Howard, 1965*a*) and the present study of the Meudon and Crimean magnetic-field data obtained during the period of the Cooperative Study of Solar Active Regions. This material comes from the period of the last solar minimum.

The following characteristics are commonly observed in developing regions:

(1) On a large scale, new regions form at the location of old weak fields. Generally regions form in old fields of leading polarity, and the appearance is that of islands of following polarity fields in extended areas of leading polarity fields which are predominant at low latitudes. In general in a complex of activity there are several regions

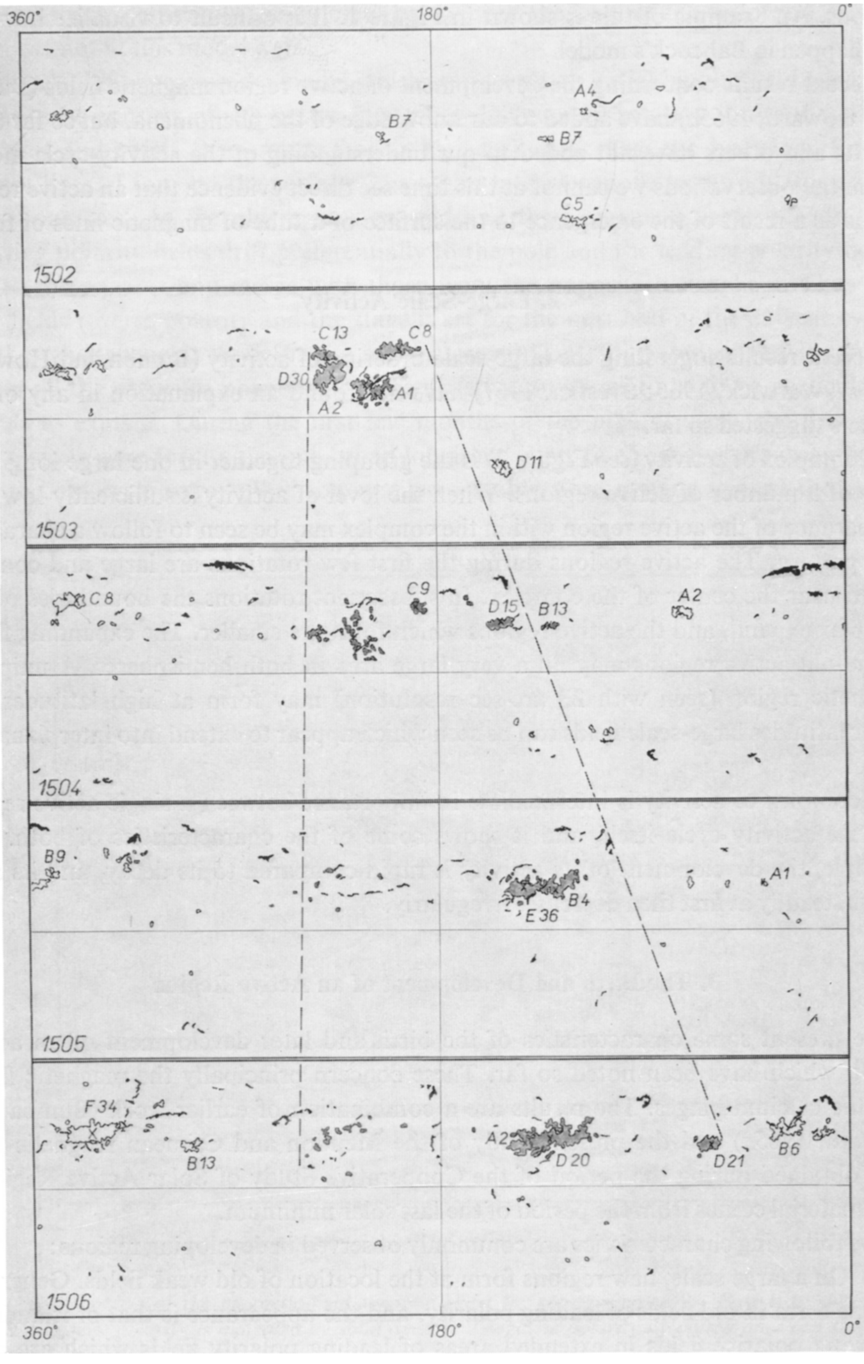

FIG. 2a. *A series of synoptic charts drawn from Fraunhofer Institute Daily Maps of the Sun. The plages associated with the complex of activity are shaded. All spot groups are indicated with their Zürich types. We have indicated the expanding boundaries of the complex by dashed lines.*

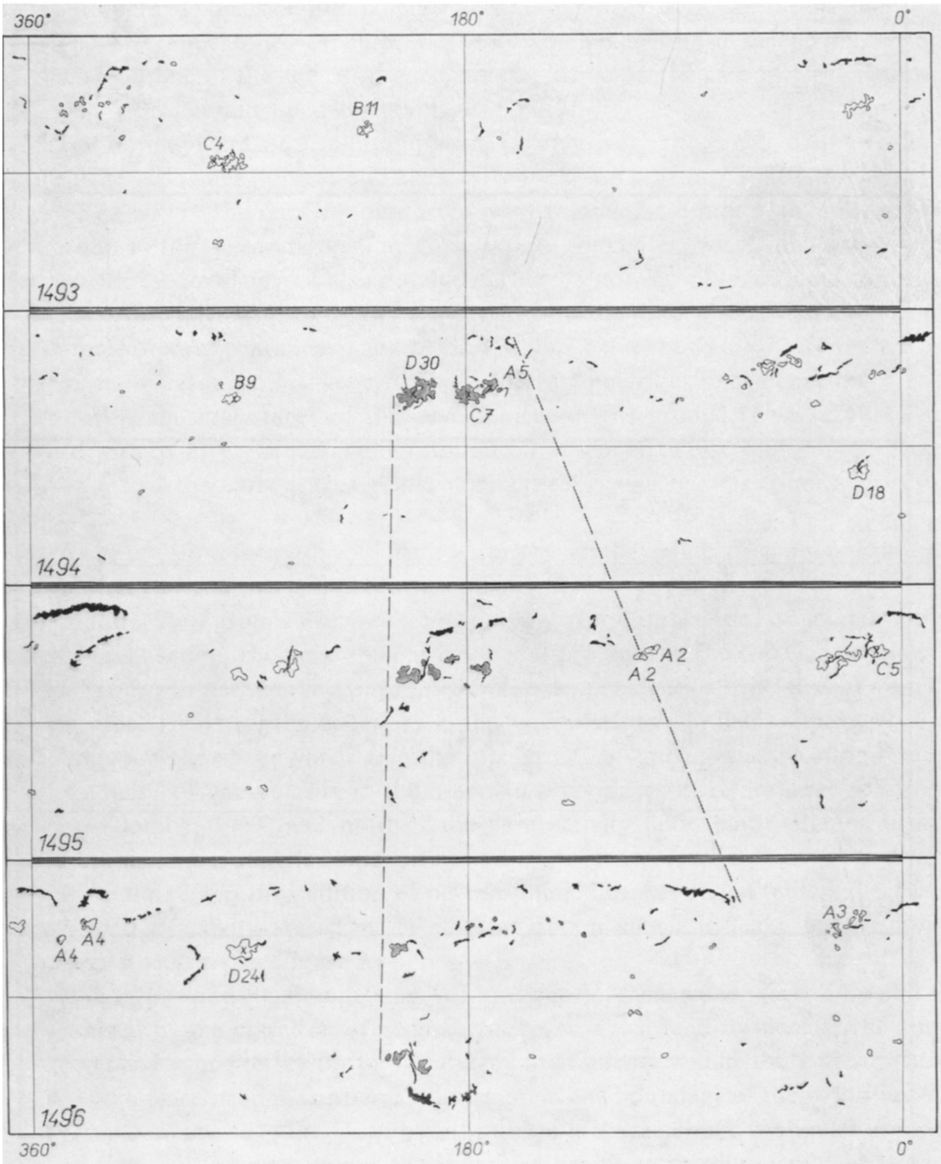

Fig. 2b. *Similar to Figure 2a for a different complex.*

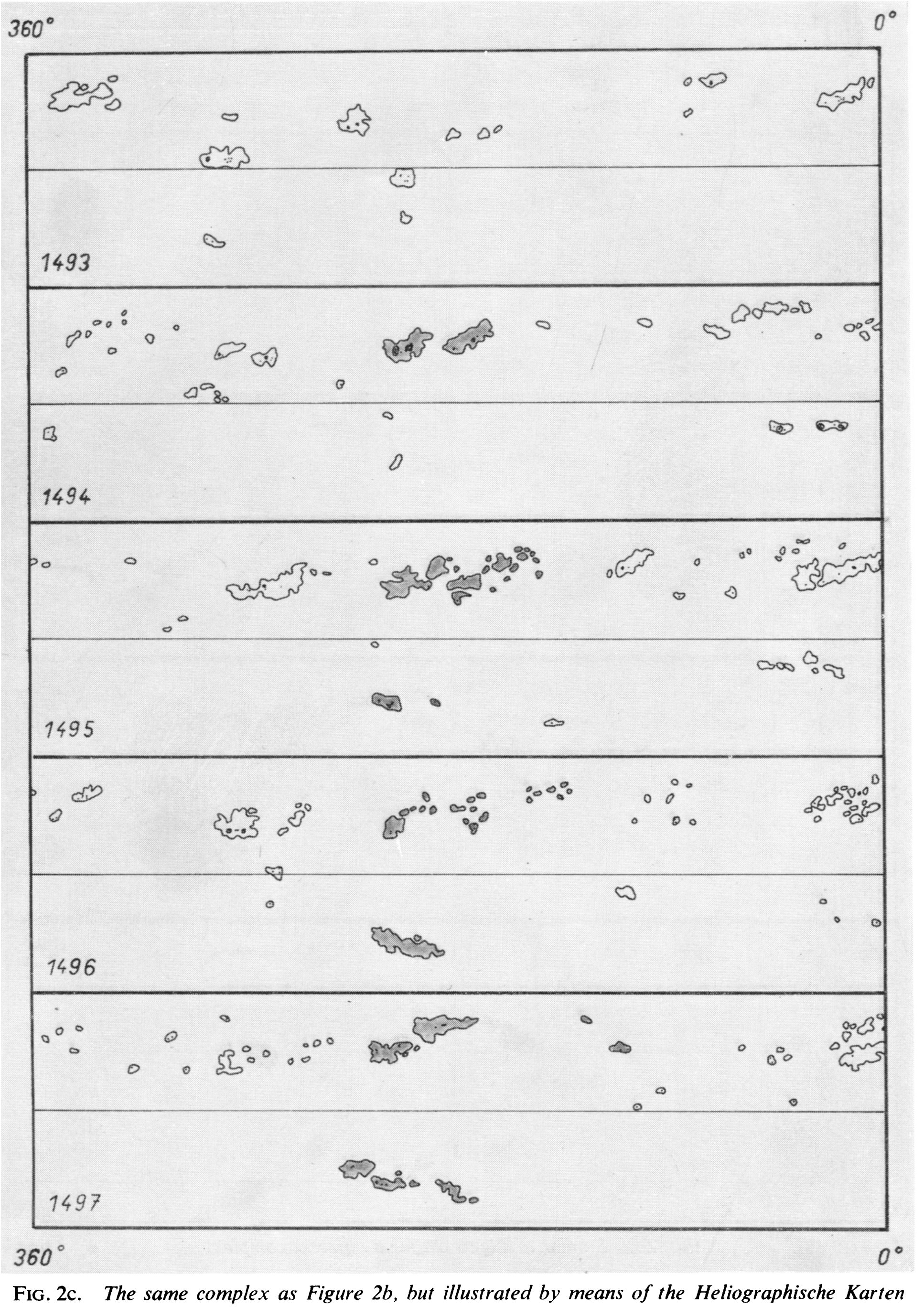

FIG. 2c. *The same complex as Figure 2b, but illustrated by means of the Heliographische Karten der Photosphere from Zürich.*

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close together. Often the following polarity fields of several regions appear to form one large feature as do the leading polarity fields. On a small scale the first brightenings of a new region appear at the boundaries of several supergranular cells – in particular at a point where old fields of both polarities meet.

(2) The first appearance of magnetic fields and plage within the young region follows the outline of the pre-existing calcium network. In the case of large regions, whole cells are eventually filled in with plage and field.

(3) The development of a region appears to start from the center of the region, move to the following portion and then to the leading portion. That is to say, the center of gravity of the region moves from what is later the center of the fully developed group to the following portion, then back to the center. When the leading part develops, the leading sunspot also develops. There is now no observational evidence one way or the other about whether the progress of the development is a motion of lines of force or an appearance of new fields.

(4) In many cases the magnetic fluxes of the two polarities appear not to be balanced during the first stages of the development of the group. These results were obtained with relatively crude angular resolution. It will be of interest to obtain more observations of the early stages of development of active regions using high resolution.

(5) As new regions form, the old fields within which they appear remain unchanged for several days. After this period the old and new fields begin to merge.

(6) In the case of groups which reach a maximum importance of C or greater in the Zürich Classification, the development in general proceeds in the following manner: for the first day or perhaps two days the development is identical with that of a small simple region. Then near the boundary of the two polarities new fields appear. Within these fields are the spots which give the region a C or greater classification. Often there is a 'gulf' of one polarity in the other. In such places there are large velocities observed (Bumba, 1963) and most of the flare activity takes place (Bumba *et al.*, 1968). At this time a complex configuration may originate. At this point in the development of the region the addition of new magnetic flux has ended (unless there is a later renewal of activity caused by the addition of new magnetic fields, and the decay of the region sets in. (See Figure 3.)

(7) The early post-maximum stage of the development of an active region is characterized by the cessation of magnetic changes which tend to increase the magnetic complexity of the region or the magnetic gradients within the region. These changes take place near the center of the region at the boundary of the polarities. At this post-maximum stage the plage often acquires a characteristic triangular appearance, and the boundary between the polarities begins to appear less complicated. Also at this stage a small filament often forms pointing to the center of the group between the polarities. This filament may later develop into a large quiescent filament.

(8) As is well known, the later stages of the development of the region are character-

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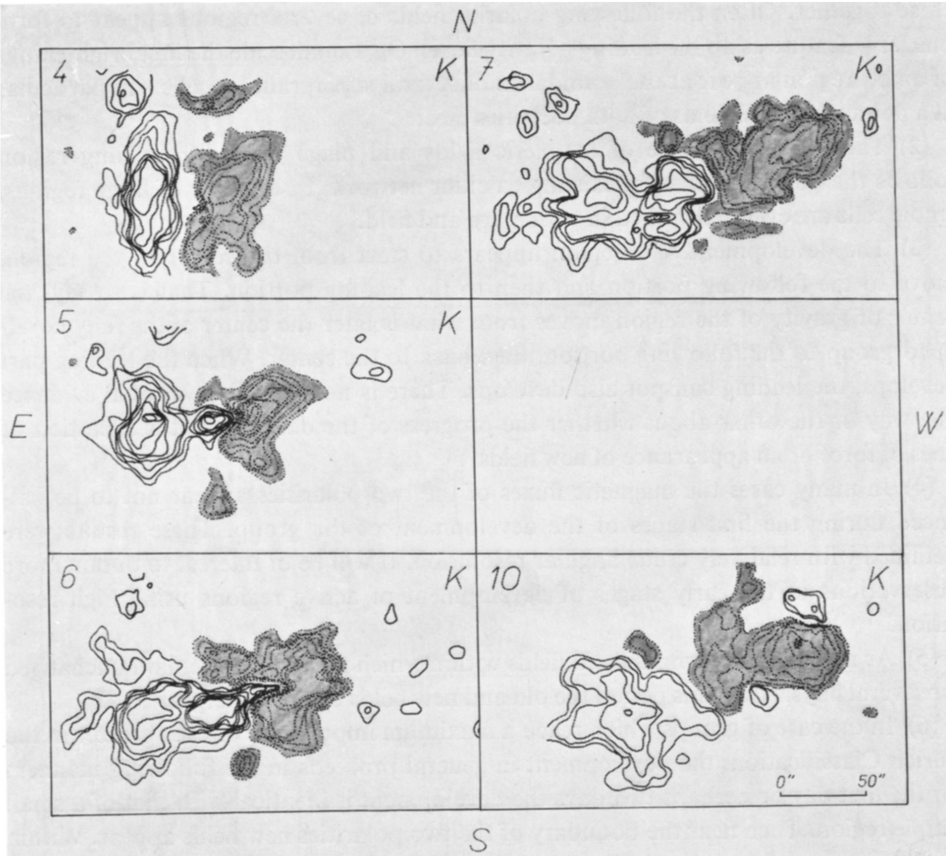

FIG. 3. *Magnetic maps of a region during September 1965. The data are from the CSSAR magnetic material from the Crimean Observatory and Meudon Observatory. The day of the month is given in the upper left corner of each map. The gauss levels are usually 10, 20, 40, 60, 100, 150, 200, 300, 400. Note the slightly complex situation that develops near the center of the group and then disappears.*

ized by the expansion of the plage, by the continuous growth of the distance between the centers of gravity of the two polarities, and by the characteristic curved teardrop shape of both the leading and the following portions. At this point, depending upon the 'density' of activity in the neighborhood of the region, the magnetic fields will either expand and weaken until they are no longer detectable, or they will merge with and become a part of the background-field pattern.

We present here an idealized chronological scheme of the shape of the magnetic fields associated with the development of a large but magnetically simple active region. (See Figure 4.) These results come mostly from the Meudon magnetic maps. This scheme refers to the stronger magnetic fields ($> \sim 50$ gauss) and the brighter portions of the plage.

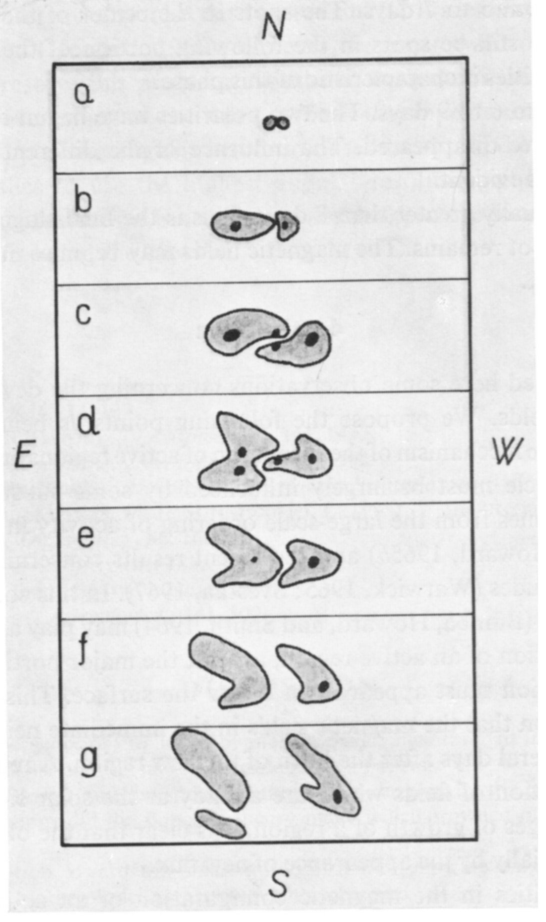

FIG. 4. *An idealized sketch of the development of an active region. The shaded portions represent the plage and the two magnetic polarities. Spots are indicated by black dots. See the text for details.*

Stage a: Age from several hours to 1 day. The first brightenings at the boundaries of supergranules.

Stage b: Age about 2 days. The development is proceeding most rapidly in the following portion of the region. The first spots have formed.

Stage c: Age from 3 to 4 days. Penumbras are formed and the group takes on a more complicated appearance. The whole field occupies an elliptical area, and the leading polarity fields lie predominantly equatorward of the following polarity fields.

Stage d: Age from 4 to 6 days. This is the start of the post-maximum phase and the boundary between the polarities is still relatively complicated. The following polarity has formed two tails to the East of the center of the region, and the plage has taken on a characteristic triangular appearance.

Stage e: Age from 5 to 7 days. The spots in the center of the group have disappeared. There may still be spots in the following portion of the plage. The 'arrow' shape of both polarities is characteristic of this phase.

Stage f: Age from 6 to 9 days. The two polarities have begun to separate, and the following spots have disappeared. The influence of the differential rotation on the shape of the fields is evident.

Stage g: Age usually greater than 8 days. This is the final stage of the spot group. Only the leading spot remains. The magnetic fields may begin to merge with the background field pattern.

4. Discussion

We have presented here some observations concerning the development of active region magnetic fields. We propose the following points as being important in an understanding of the mechanism of the formation of active regions and of the cycle itself.

(1) The solar cycle must be largely influenced by some subsurface phenomena. This conclusion comes from the large-scale ordering of activity in complexes of activity (Bumba and Howard, 1965*b*) and the recent results concerning the distribution of activity in longitudes (Warwick, 1965; Švestka, 1967). In this connection the 'giant supergranular cells' (Bumba, Howard, and Smith, 1964) may play a role.

(2) In the formation of an active region, at least the major portion of the magnetic flux of the new region must appear from below the surface. This conclusion comes from the observation that the magnetic fields in the immediate neighborhood remain undisturbed for several days after the birth of the new region. A region does not form from the redistribution of fields which are already at the solar surface. Even in the case of the later stages of growth of a region, it is clear that the older magnetic fields are undisturbed initially by the appearance of new flux.

(3) The complexities in the magnetic configuration of an active region develop within the first few days of the birth of the region. Unless there is a later renewal of activity (which may also produce a magnetically complex situation), the tendency after the maximum phase of the development of the region is for the magnetic configuration to become simple. The analogy in the large scale is the formation of regular features in the background-field pattern.

The following questions concerning solar activity present themselves at this point and appear to be of interest. More observations are needed to clear up these matters.

(1) What happens to the large-scale field formed by the expansion of old active regions? A large amount of flux appears to head toward the poles, but this flux is not observed to collect at the poles, and we know very little of what happens at the polar regions.

(2) Does the characteristic shape seen in the evolution of active regions imply an angular velocity of rotation which is greater for stronger fields than for weaker fields – and thus perhaps imply an influence from deeper layers?

(3) Is the fine scale structure of the magnetic field giving us on the large scale of the

resolution of our observations, false data on net fluxes? It seems unlikely that this can be a very great effect (Howard, 1966); however, we must await observations of very high resolution to resolve this problem. Naturally, because of the fine-scale structure of magnetic fields over much of the solar surface, the appearance of a magnetogram depends markedly upon the angular resolution used to obtain the observation. While in general one wishes to use the highest angular resolution possible, for problems involving large-scale features it is sometimes desirable to use low resolution in order to see the 'forest' instead of the 'trees'.

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DISCUSSION

Winckler: Is the emergence of flux loops by magnetic buoyancy thought to apply to BMR's or to the spots themselves? This point is not clear in Babcock's papers.

Howard: Both the BMR's and the spots are thought to develop by the emergence of flux tubes.

Acton: What predictions did the Babcock theory make which provided observational tests of the theory?

Howard: The migration toward the polar latitudes of the following magnetic flux of old active regions was predicted by the model and subsequently observed.

Bumba: The observers are in great difficulties to say something more about the observation of emerging flux ropes. If we observe with a lower resolution, we may see very nicely the distribution of magnetic field in two polarities and this distribution may be represented by a model of outcoming tube of magnetic field. But if we observe with high enough resolution we do not see such well-organized picture any more, we then have a complicated situation which we cannot represent by a simple model of buoyant flux rope.

Sturrock: If sunspots always form adjacent to neutral lines, they may represent the emergence of new flux. If sunspots may form far from a neutral line, these spots must be formed by the gathering together of field lines which emerged earlier in the development of the active region. Do sunspots always form adjacent to neutral lines?

Howard: No, they do not, so it appears that the spots must form from the new plage magnetic fields.

Severny: How is your feeling about unipolar magnetic regions? We have got convinced from our observations with high resolution on Crimean magnetograph that these regions disappear when we use high resolution ($2''.5 \times 4''$) and they consist of a number of small elements of different polarity (I mean the first part of your talk relating to the local weak magnetic fields).

Howard: Do you think that even magnetic flux over these regions can be zero?

Severny: Yes. Because the signal of magnetograph is proportional to the field strength and the area of an element and this signal must be higher than noise level to be recorded. If the area is small enough the signal can drop below noise level even for strong field and this element can be omitted at the records. So the excessive flux of one sign could in principle be partly compensated by small elements of opposite sign.

Howard: Our observations at high resolution do not indicate that the UM flux disappears. Such an effect could well get us out of the problem of what happens to the flux that moves toward the poles, but even if there were no net flux, the UM's would be obviously of some physical significance since they are clearly observed to have shape and motion.

Bumba (to Severny's question): We are using the terms BMR and UMR in the same sense as they were used for the first time by Babcock. If we were to take into account the fine structure of the magnetic field, we must speak only about the complex magnetic fields.

Nussbaumer: Where do you put the division between high and low resolution and how good is the best resolution you can obtain?

Howard: Our best resolution is 2 arc-sec, and I would put the dividing line between high and low resolution for magnetographs at about 10 arc-sec.

Wilcox: Professor Severny has correctly pointed out that the so-called unipolar photospheric magnetic fields contain a complicated structure having fields of both polarities when examined at high resolution. However, it seems that the concept of a 'unipolar' region is still valid if this is defined to mean a large region throughout which the net magnetic flux (as observed with a slit size of perhaps 23″) is of a single polarity. Such 'unipolar' regions seem often to be the sources of interplanetary magnetic-field sector structures within each of which the field polarity is unidirectional.

Bappu: Am I correct in assuming that your magnetic-field representation refers only to the longitudinal case? Have you examined the transverse fields in such developing regions?

Howard: Our observations are only of the longitudinal component of the field. We have no means at present of observing the transverse component.

Jäger: If one observes an active region on the one hemisphere, often one observes a similar region on the other at nearly the same latitude and longitude. Can you derive from your observations how often this occurs in the average?

Howard: I do not know, and I also do not know whether the occurrence of two AR's at about the same time at the same longitude in two hemispheres is due to chance or implies some deep-rooted connection.

Jensen: I have a question related to the prediction one can make from the idea of magnetic buoyancy. If the field is formed in this way, the direction of the field should change from horizontal to vertical during the development. Is there any observational evidence for such a change?

Howard: I am not aware of the existence of such observations, but perhaps we shall hear of some recent observations during this symposium.

McIntosh: White-light observations show linear dark features, lanes in the photosphere, during the growth of bipolar sunspot groups, and emergence of new spots in large groups. If we interpret these dark linear features as analogous to the dark penumbral structures then it appears that the emergence of a strong transverse field accompanies the growth of a sunspot.

Sturrock: My colleagues at Stanford have carried out an analysis of sunspot data to determine whether there is any correlation between the appearance of another AR at about the same longitude in the hemisphere. We find that there is no statistically significant correlation.