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ON THE STRUCTURE OF  
THE SUNSPOT ZONE

*by* BARBARA BELL



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*Smithsonian Institution.*

Cambridge, Mass.

# On the Structure of the Sunspot Zone

By BARBARA BELL<sup>1</sup>

Just over a century ago Carrington discovered that the distribution of sunspots shifts in latitude during the sunspot cycle. The general features of this latitude shift are best exhibited by Maunder's (1904, 1913) famous butterfly diagram, recently brought up to date (Greenwich, 1955). The first sunspots of a cycle appear in latitudes 20–30° north and south. The zone of maximum spottedness moves toward the equator during the eleven-year sunspot cycle. The last spots occur between 2° and 8° from the solar equator. Waldmeier (1939) has determined the average rate of this equatorward drift to be 2° per year.

While these general features of this shift in latitude have long been among the best known facts about sunspots, the cause of the displacement remains among the least understood of solar phenomena. The process can be pictured in several ways:

(1) A single zone, generating a single frequency distribution of spots, exists in each solar hemisphere, and drifts toward the equator at a rate of 2° per year.

(2) Two or more zones develop in each hemisphere, each drifting equatorward.

(3) Several zones of activity develop in each hemisphere, and each remains stationary in latitude, but they are just sufficiently out of phase to simulate a latitude shift.

Lockyer (1904) argued that the law of spot zones, discovered by Carrington and corroborated by Spoerer, represented only a very general idea of a complicated pattern of sunspot circulation and left many anomalies unexplained. In an effort to obtain a more exact representation, he grouped the data in 3° intervals of mean daily sunspot areas, formed yearly sums, and found "several centers of spot action" each year. He connected the peaks of activity in successive years in such a way that each center migrated toward the equator; he thereby found three to four "spot activity tracks"

along which move the centers of spot disturbance.

Maunder (1904) immediately criticized Lockyer's peaks as a meaningless consequence of assigning the areas of large spot groups to a specific 3° interval of latitude, when in fact the largest groups extend over as much as 6° to 10°. Maunder argued for the concept that a single frequency distribution occurs in each hemisphere, and his picture has long been the most generally accepted.

Recently, however, Becker (1954a) revived the question whether the conventional butterfly diagram is adequate for a quantitative analysis of spot zones. He determined the number of spot groups per 2° latitude interval per year for sunspot cycles Nos. 12–18, covering the years 1880–1954. To take account of the latitude drift and to determine the mean shape of the distribution of spots with latitude, he introduced a shift of 2° from one year to the next and summed the numbers of spots. The resulting mean distribution gave evidence that the center of the spot zone in each solar hemisphere coincides with a region of subnormal sunspot activity. Becker pointed out further that the position of this dip coincides with a division in the direction of proper motions of sunspots—a division between equatorward and poleward proper motions (Becker, 1954b). Thus he concluded that each hemisphere's spot zone is composed of two subzones, each drifting toward the equator at 2° per year.

From sunspot data obtained at Mount Wilson, and listed on IBM cards, Glazer and I, in 1955, computed the annual sum of  $H$  (the maximum magnetic field strength observed in a sunspot group) for each degree of latitude for the years 1937–1953. An examination, some time later, of the computations for the 1937 cycle (see figs. 1c, 3) strikingly suggested the hypothesis that several stationary nondrifting

<sup>1</sup> Harvard College Observatory, Cambridge, Mass.

zones occur in each hemisphere, as proposed in the third concept listed above. The pattern for the 1947 cycle (fig. 2*a*) however, was much less clear.

Subsequently I extended the summations of  $H$  back to 1917, the year when Mount Wilson began systematic observations of sunspot field strengths, and forward through 1958. Also I determined the number of spot groups per year at each degree of latitude, both from Mount Wilson data and from the Greenwich Photoheliographic Results for 1912–1955. Greenwich sunspots “seen on one day only” were not included in the tabulations. While the original tabulations were made for each degree, all results shown here are based on either  $2^\circ$  sums or  $2^\circ$  running means.

The resulting distributions of maximum magnetic field strengths,  $H$ , for individual years appear in figures 1, 2; for the individual sunspot cycles in figure 3; and for all the years, from 1917 through 1958, in figure 4. Figures 5 and 6 show the distributions in numbers of spot groups observed at Mount Wilson; figures 7 and 8 exhibit the numbers of groups observed at Greenwich.

One can see immediately from figures 1–8 that the evidence for multizonality is stronger in the Mount Wilson data than in the Greenwich numbers. Moreover, the evidence is stronger in the magnetic field strengths than in the numbers of spot groups. The 1937 cycle (No. 17) shows the most striking impression of multizonality, while the 1947 cycle gives the smoothest distribution.

Although the first tabulations were made by IBM machines, the remainder were carried out by hand. During this manual tabulation I obtained a strong impression that the latitude of maximum activity does not move smoothly, as might be expected from the slow drift of a single zone or even of several zones. Rather, the zone of maximum activity seems to jump from one latitude to another several degrees away, as though several narrow belts of activity existed, waxing and waning in turn.

Various difficulties arise when one attempts to test the statistical significance of the fluctuations in the latitude distribution curves. A smooth curve was drawn through  $5^\circ$  running means for each cycle and for the total period

covered by the observations, and the chi-square method was used to test the significance of the deviations from this smooth curve. Such tests cannot be considered rigorous or exact, because uncertainty exists as to the number of degrees of freedom appropriate to such empirical, hand-

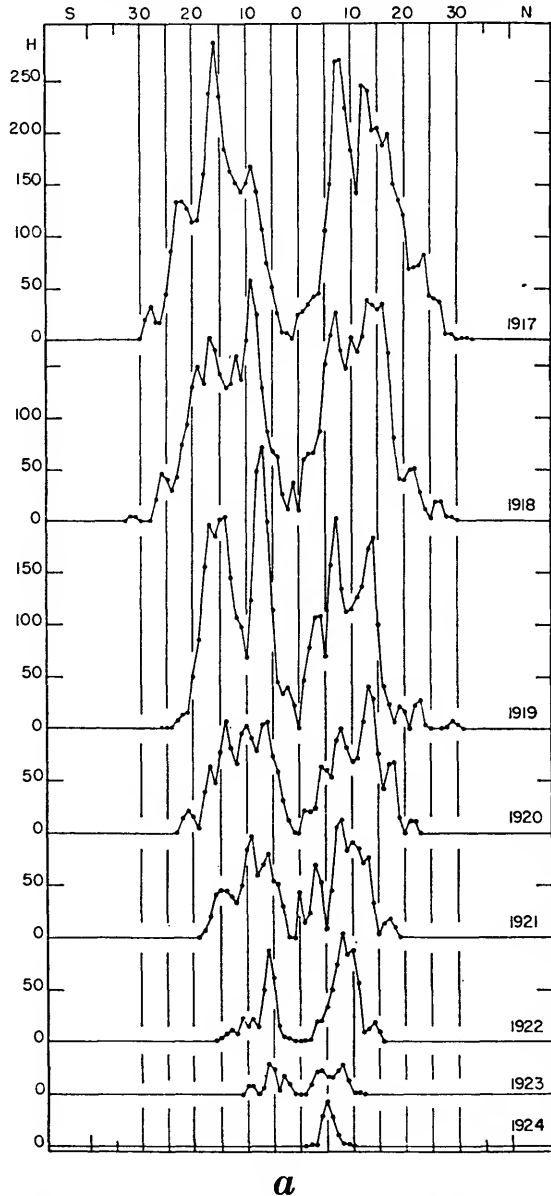


FIGURE 1.—Distribution with latitude on the sun of total magnetic field strength ( $H$ ), plotted in  $2^\circ$  running means and units of 100 gauss, of sunspots in cycles 15–17: *a*, No. 15 (1917–1924); *b*, No. 16 (1923–1935); *c*, No. 17 (1934–1945).



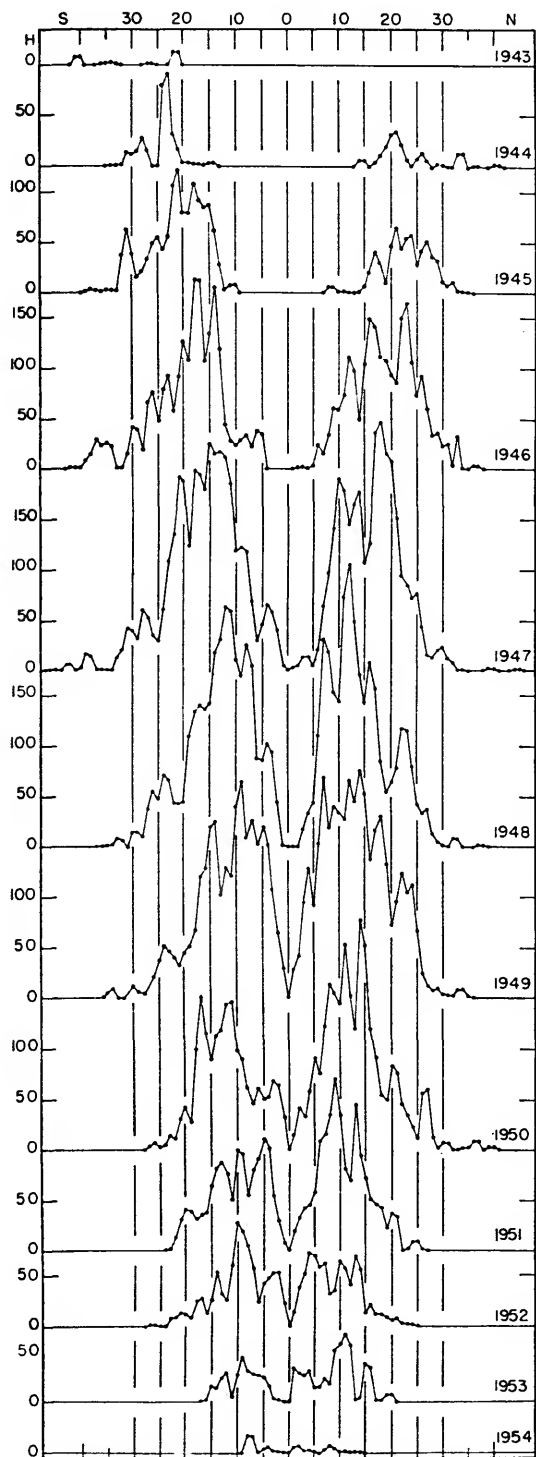
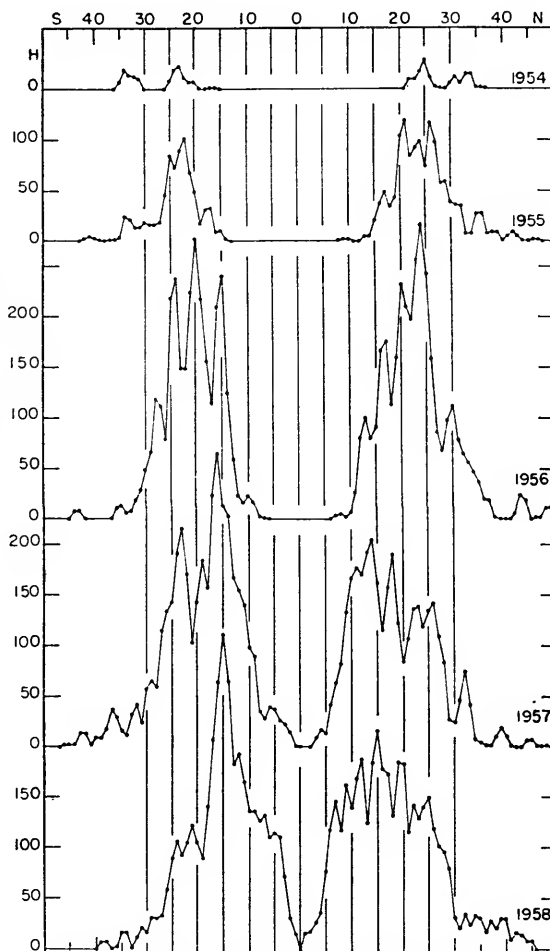
*a**b*

FIGURE 2.—Distribution with latitude on the sun of total magnetic field strength ( $H$ ), plotted in  $2^\circ$  running means and units of 100 gauss, of sunspots in cycles 18 and 19: *a*, No. 18 (1943–1954); *b*, No. 19 (1954–1958).

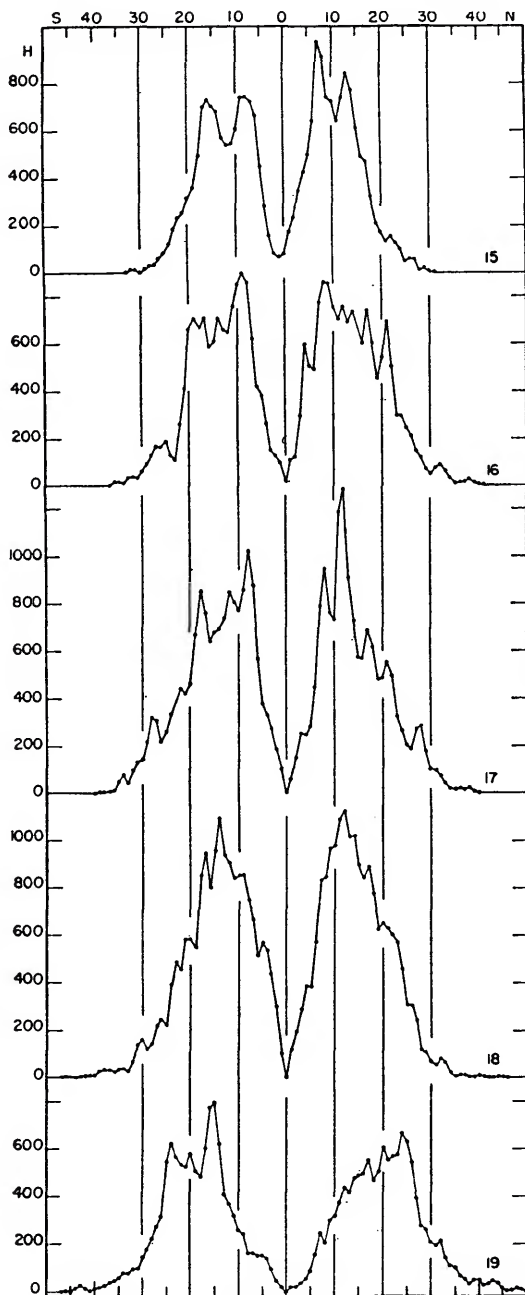


FIGURE 3.—Distribution with latitude on the sun of total magnetic field strength ( $H$ ), plotted in  $2^\circ$  running means and units of 100 gauss, of sunspots in cycles Nos. 15-19 (1917-1958).

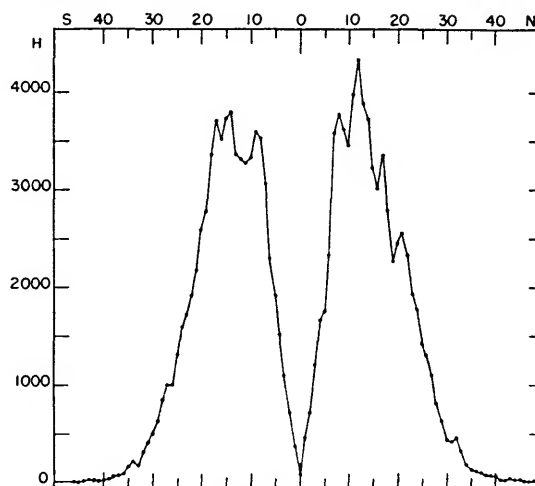


FIGURE 4.—Distribution with latitude on the sun of total magnetic field strength ( $H$ ), plotted in  $2^\circ$  running means and units of 100 gauss, of sunspots for the period 1917-1958.

drawn smooth curves. For these tests, however, I set the number of degrees of freedom, as a best guess, at three less than the number of  $2^\circ$  sums entering the test; that is, at  $N-3$ .

When the test is applied to numbers of Greenwich sunspot groups (figs. 7, 8), the hypothesis that the fluctuations are of a random nature is not contradicted. Greenwich data provide no statistically persuasive evidence for other than random deviations from a smooth variation with latitude.

For numbers of spot groups observed at Mount Wilson, on the other hand, the chi-square test gives some probabilities so small that one need not be disturbed by an uncertainty of one or two in the number of degrees of freedom. Several tests were made. With the combined data from the northern and southern hemispheres, the probability that fluctuations as large as the observed ones would arise by chance was about 1 in  $10^4$  (or  $P \sim 10^{-4}$ ) when odd  $2^\circ$  sums ( $1+2^\circ$ ,  $3+4^\circ$ , etc.) were used. With even sums ( $2+3^\circ$ ,  $4+5^\circ$ , etc.), however, the fluctuations were barely significant, with  $P \approx 0.05$ . The reason for this difference appears to be that the significance of the fluctuations arises primarily from the subsidiary peaks at



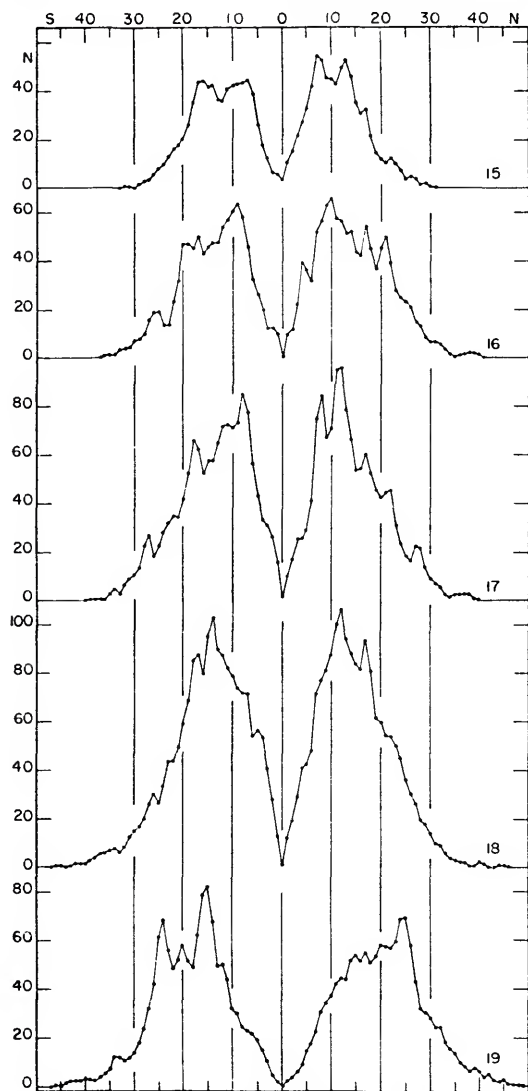


FIGURE 5.—Distribution with latitude on the sun of numbers ( $N$ ) of sunspot groups, plotted in  $2^\circ$  running means, for sunspot cycles Nos. 15–19; data obtained from observations made at Mount Wilson in the years 1917–1958.

$7-8^\circ$  and  $17-18^\circ$ , which contribute more effectively when combined in the odd manner (i.e., not split into  $6+7$  and  $8+9$ , etc.).

If the spot numbers for the northern and the southern hemispheres are tested separately, by comparison with a single mean smoothed curve, the probabilities for chance occurrence of the observed fluctuations become 1 in  $10^5$  for the northern and 1 in 500 for the southern hemisphere ( $P \sim 10^{-5}$  and 0.005); and  $P \sim 10^{-7}$  for

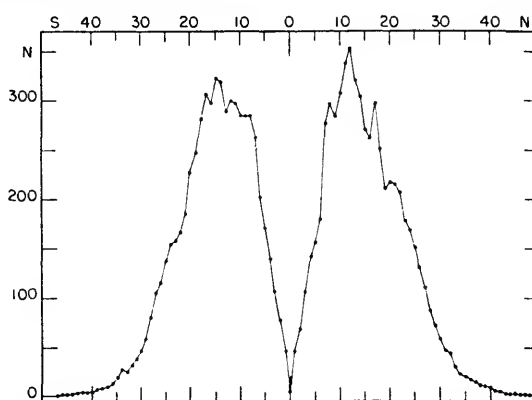


FIGURE 6.—Distribution with latitude on the sun of total numbers ( $N$ ) of sunspot groups, plotted in  $2^\circ$  running means; data obtained from observations at Mount Wilson in the years 1917–1958.

north plus south. If the numbers for north and south are tested separately and each compared to its own smooth curve, one obtains  $P \sim 10^{-5}$  for the north,  $P \sim 0.5$  for the south, and  $P \sim 10^{-3}$  for north plus south. Thus the evidence for non-randomness is impressive only for the northern solar hemisphere.

Tests of the Mount Wilson numbers for individual sunspot cycles (fig. 5) indicate that the fluctuations in cycles 15 and 18 are not statistically significant. Cycle 16 gives  $P \sim 0.02$ , and cycle 17 gives  $P \sim 0.001$ .

Properly, chi-square tests are of course not applicable to measures of intensities, such as magnetic field strengths. However, to obtain some approximate idea of the significance of the variations in the field-strength curves (figs. 3, 4), I normalized  $H$  to  $H'$  so that the total number of spots,  $N$ , equaled total  $H'$ , thus making the units in  $H'$  comparable to those in spot numbers. Chi-square tests on  $H'$  gave  $P < 10^{-10}$  with north and south combined throughout the test; odd sums were used. When the solar hemispheres were tested separately, and each compared with its own smooth curve, the north gave a probability  $P < 10^{-8}$ , the south gave  $P \sim 0.08$ , and north plus south gave  $P < 10^{-7}$ , that the fluctuations are of a random character.

Thus, statistically, the field-strength data provide more persuasive evidence for multipolarity than do numbers of spot groups. The evidence from Mount Wilson numbers is



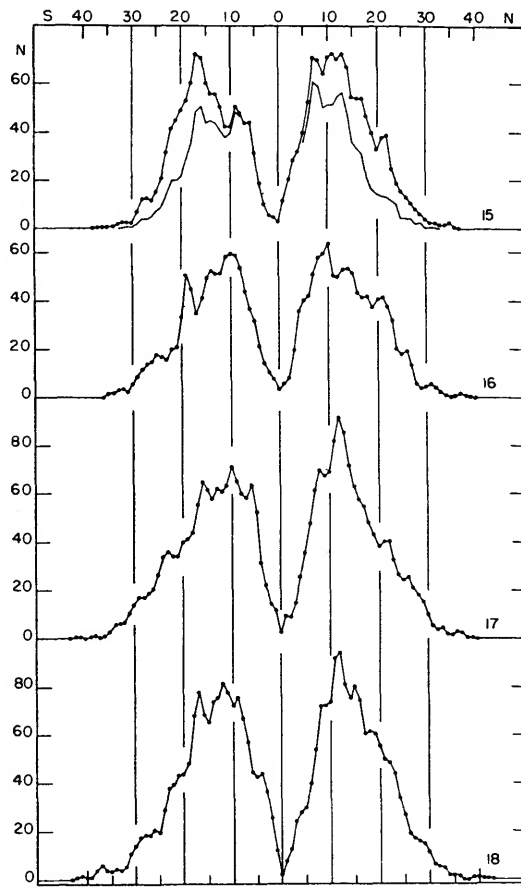


FIGURE 7.—Distribution with latitude on the sun of numbers ( $N$ ) of sunspot groups, plotted in  $2^\circ$  running means, for sunspot cycles Nos. 15-18; data obtained from Greenwich observations for the years 1912-1954.

better than that from Greenwich numbers. In Mount Wilson data the evidence is stronger by far in the northern than in the southern solar hemisphere. Most of the statistical significance arises from the major secondary peaks at  $7-8^\circ$  N and  $17-18^\circ$  N.

These results make it impossible to distinguish conclusively among the three pictures of the sunspot zone and its latitude shift, from presently available observations alone. We shall need further and different observations, and/or a theory based on one of the hypotheses which will satisfactorily explain the apparent shift of the zone(s) over the cycle. On the other hand, the probability that the northern hemisphere distributions could arise

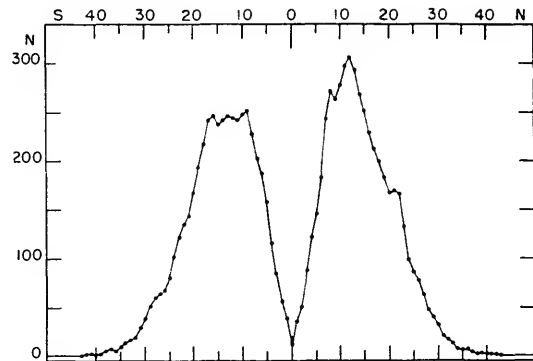


FIGURE 8.—Distribution with latitude on the sun of total number ( $N$ ) of sunspot groups, plotted in  $2^\circ$  running means; data obtained from observations at Greenwich in the years 1912-1954.

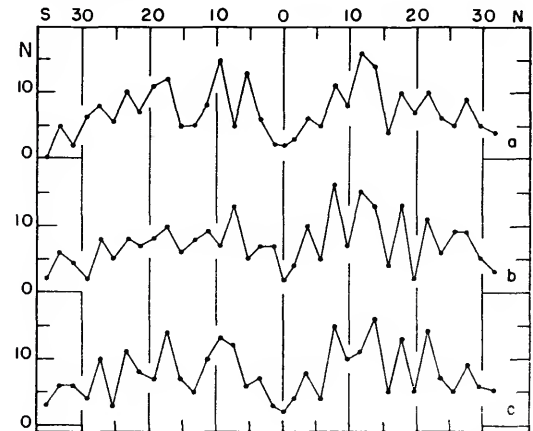


FIGURE 9.—Number ( $N$ ) of local maxima in  $2^\circ$  sums, at various solar latitudes, derived from: *a*, Greenwich numbers of sunspot groups for the years 1912-1954; *b*, Mount Wilson numbers of sunspot groups, 1917-1955; *c*, sunspot magnetic field intensities, 1917-1955.

by chance is so small that theoreticians would seem justified in seriously exploring the multizonal concept of sunspot activity. The low probability may justify also some further discussion of the data here compiled, in the light of such a concept.

If we are to accept a multizonal picture even tentatively, we should be able to say with some confidence where the maxima and minima of the subzones lie. I have already referred to the subsidiary maxima at  $7-8^\circ$  and  $17-18^\circ$ , which contribute the largest chi-square deviations found in the Mount Wilson data. From the location of these peaks and from the curves shown in figures 3-6, one can conclude that

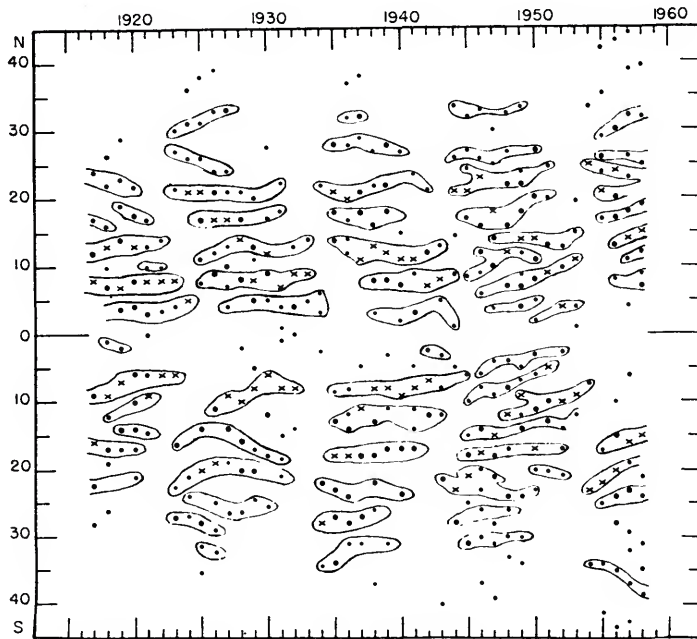


FIGURE 10.—Caterpillar diagram, illustrating the multizonal concept of sunspot activity. The dots and crosses represent the peaks in the curves of figures 1, 2, plotted at the appropriate year and solar latitude. The crosses locate the highest peaks of the year; the dots represent the secondary peaks and vary in size roughly according to their importance. The caterpillars enclose peaks postulated to belong to a single narrow activity zone. (A second graph of local minima was used to help locate the boundaries, and accounts for many of the seemingly arbitrary wiggles.)

the apparent maxima of spot activity lie at latitudes between the multiples of  $5^\circ$ , with local minima approximately at the multiples of  $5^\circ$ . In the north the principal maximum lies at  $12\text{--}13^\circ$ , with a third secondary peak clearly visible at  $21\text{--}22^\circ$ .

The subzones can be located also by study of the  $2^\circ$  nonrunning sums. On a graph of time against solar latitude, I plotted the latitudes of peaks and subpeaks for each year, for both Greenwich and Mount Wilson data. The number of peaks in each latitude interval was counted, with the results shown in figure 9. Two to three times more maxima occur at some latitudes than at others, and most of these peaks fall clearly between the multiples of  $5^\circ$ . In this respect the patterns from Greenwich and Mount Wilson data agree fairly well. Again, the northern solar hemisphere shows a more orderly pattern than the southern hemisphere.

Figure 10 shows the location of peaks derived from the  $2^\circ$  running means of total  $H$ ; that is, from the data of figures 1, 2. Because running means permit more wobbling in the position of the local peaks, they do not locate the zones as clearly as do the  $2^\circ$  nonrunning sums employed in figure 9. To illustrate more vividly the multizonal concept, on figure

10 I have drawn curves enclosing maxima which might reasonably be considered as springing from a single belt of activity. In contrast to the famous butterfly diagram, figure 10 might be termed a "caterpillar diagram." A second graph, of the local minima, was used as a guide in determining which belt a given point seemed to belong to; thus the outlines of the individual caterpillars are somewhat less arbitrary than they might at first appear to be.

Figure 11 shows the number of spot groups, and figure 12 the amount of magnetic field strength (in percentage of total  $H$  in the hemisphere for the given sunspot cycle), per  $5^\circ$  zone of latitude per year. The principal reason for plotting  $H$  in percentages is that the average value of  $H$  appears to have changed during the years under study (see Bell, 1959). The average magnetic field strength is larger for cycles 15 and 16 than for subsequent cycles, as may be seen from the composite  $N$  and  $H$  curves in figures 13 and 14. Figure 15, showing the mean annual spotted area (Greenwich, 1955), indicates a similar decrease in the ratio of field strength to area. Nicholson (personal communication) advises that this decrease may possibly result from changes in observing procedure at Mount Wilson.

Differences between the Mount Wilson and

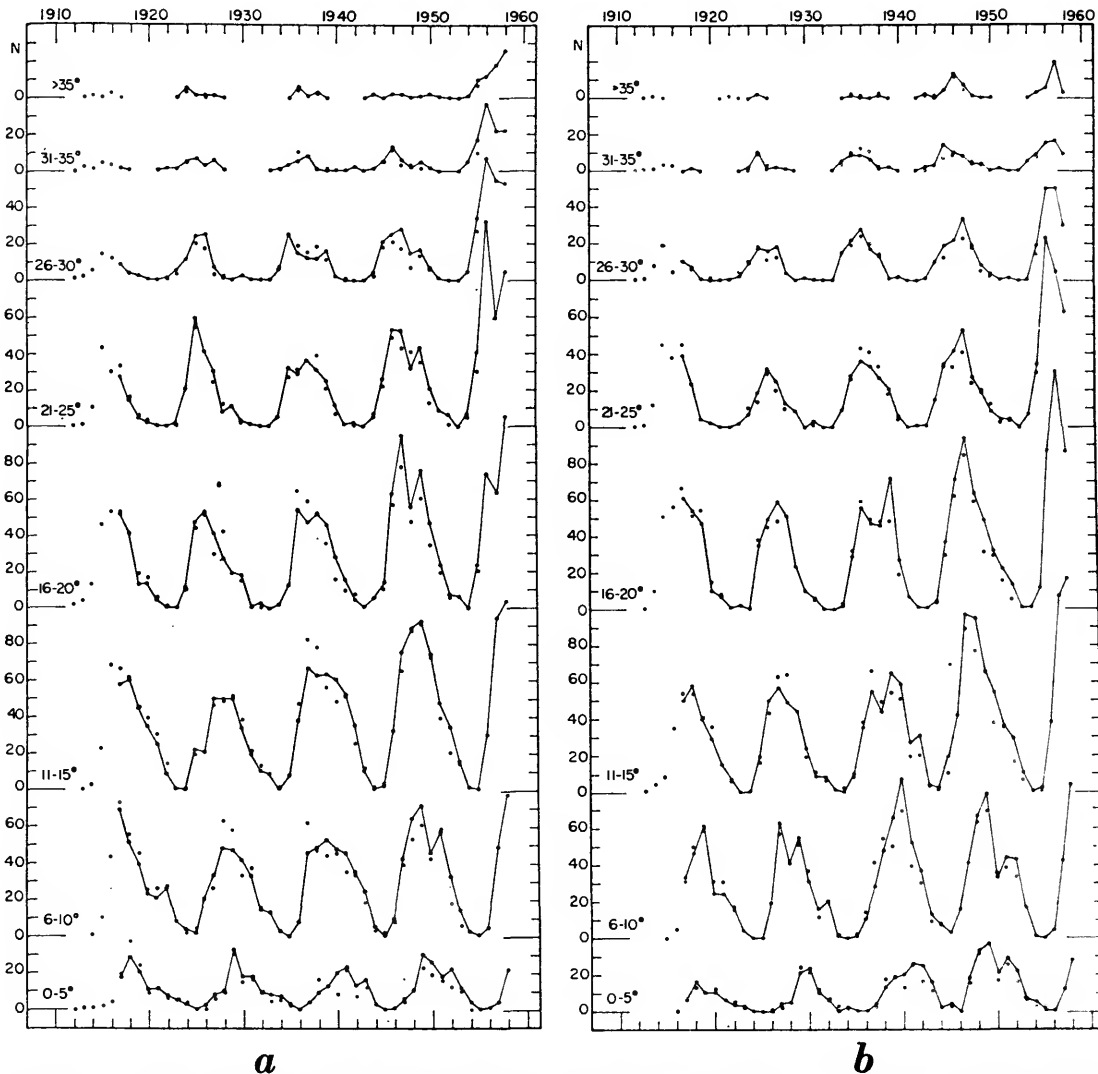


FIGURE 11.—Number ( $N$ ) of spot groups per year in each  $5^\circ$  zone of heliographic latitude. Solid line, Mount Wilson data; open circles, Greenwich data. *a*, In the northern solar hemisphere; *b*, in southern hemisphere.

Greenwich numbers of spot groups (figs. 11, 13) can be accounted for by the fact that Greenwich sunspots "seen on one day only" and Mount Wilson spots without published field strengths were omitted from this study. Completeness of the  $H$  data for small spots, of 100–200 gauss or so, varies from year to year.

In figures 11 and 12, note the great enhancement of spot activity in the higher latitudes, which appears more or less simultaneously in the northern and southern hemispheres during the present sunspot cycle (No. 19). Since

cycles characterized by high sunspot numbers tend also to show a rapid rise to maximum (Waldmeier, 1935), perhaps unusually vigorous activity in the higher latitude subzones may be necessary for the occurrence of an unusually high sunspot maximum.

From figures 1, 2, and 12 one can see that the subzones have a retardation in phase of about one year per  $5^\circ$ , or one year per zone. This fact suggests the interesting speculation that the reversal of the general magnetic field of the sun, recently found by Babcock (1959),

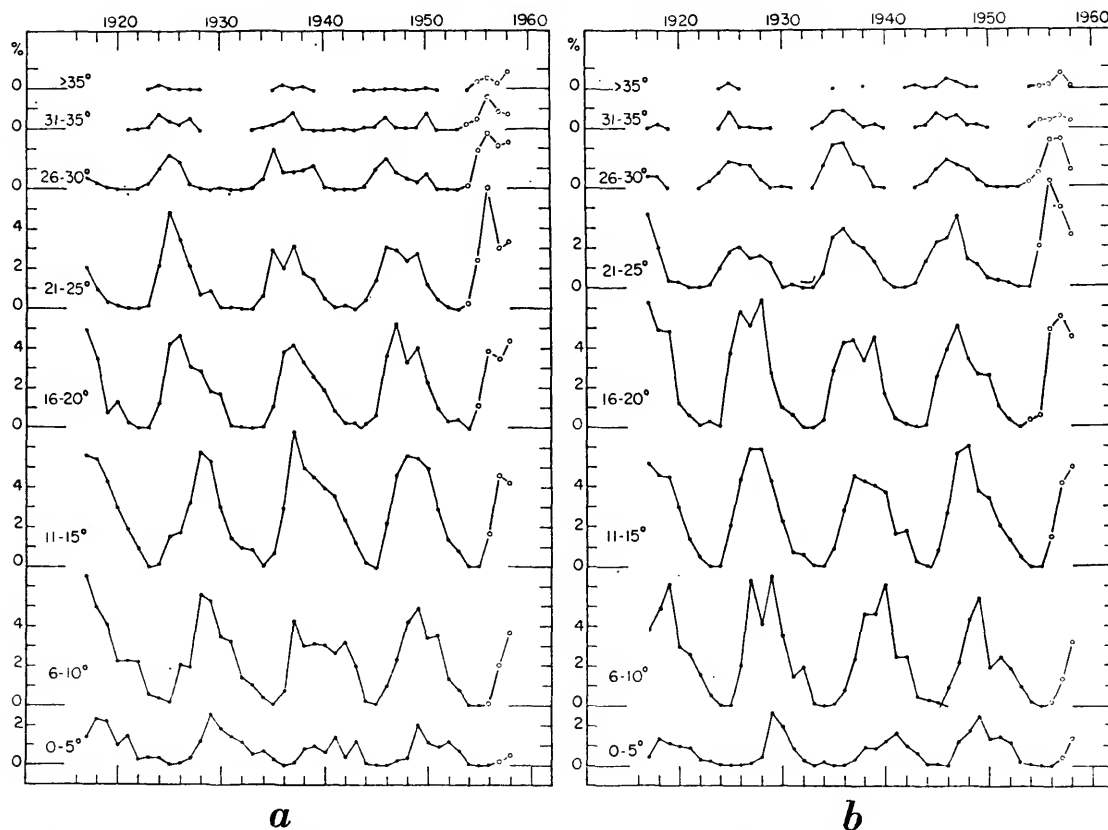


FIGURE 12.—Percentage of magnetic field intensity ( $H$ ) of sunspots in each  $5^\circ$  zone per year. Percents are taken relative to the total  $H$  observed at Mount Wilson in the particular cycle and hemisphere. (Total  $H$  for cycle No. 15 was estimated from Greenwich spot numbers, for cycle No. 19, arbitrarily taken as 20,000 for each hemisphere, about 12 percent above that observed in cycle No. 18; the points of cycle No. 19 are shown as larger open circles with broken lines.) *a*, In the northern solar hemisphere; *b*, in southern hemisphere.

might be considered as a manifestation of the phase lag at high latitudes. In 1953, late in cycle No. 18, the sun's general magnetic field had a polarity opposite to that of the lead spots in the respective hemispheres. At the start of the new cycle the lead spots and the general field had the same polarity. After the reversal of the general field in 1957–58, the polarities of the general field and the lead spots were again opposite, as if cycle No. 20 had already begun at the poles. The polar faculae appear also to have their maximum frequency around the time of the general sunspot minimum, being thus perhaps in phase with the general field.

This paper may have raised more questions than it has answered. However, the observations now available apparently do not permit any decisive choice among the available con-

cepts of the sunspot zones. Perhaps a more detailed study of local magnetic fields would be useful.

Menzel (personal communication) has pointed out that if the fluctuations in spottedness with latitude are real and meaningful, the significant aspect may be the minima rather than the maxima. Instead of belts of greater activity, the sun may have regions of suppression in a single zone—in the manner of zonal harmonics. Only intensive theoretical work can resolve these questions.

#### Acknowledgments

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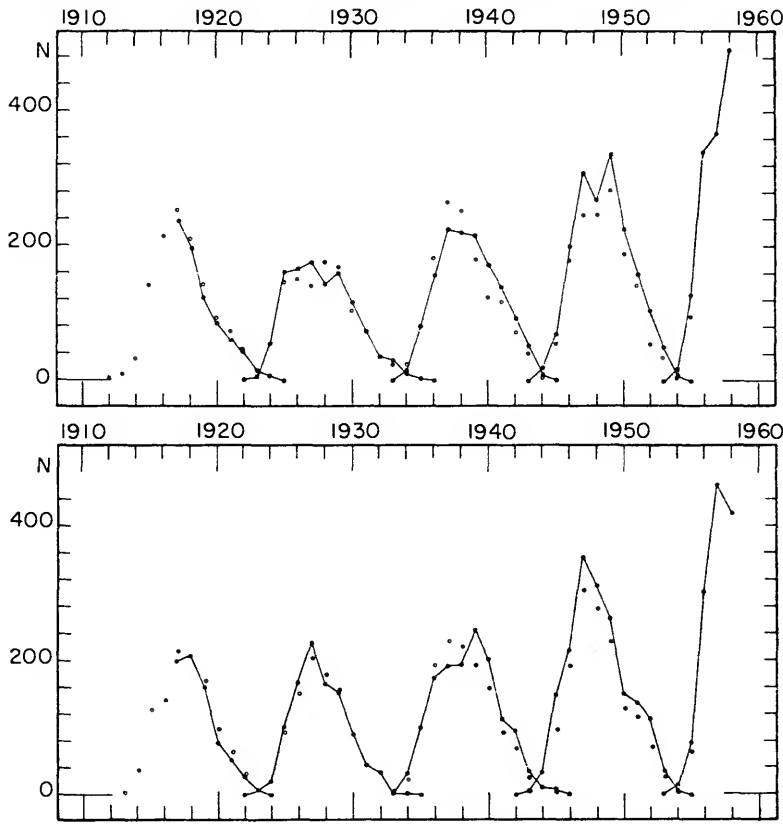
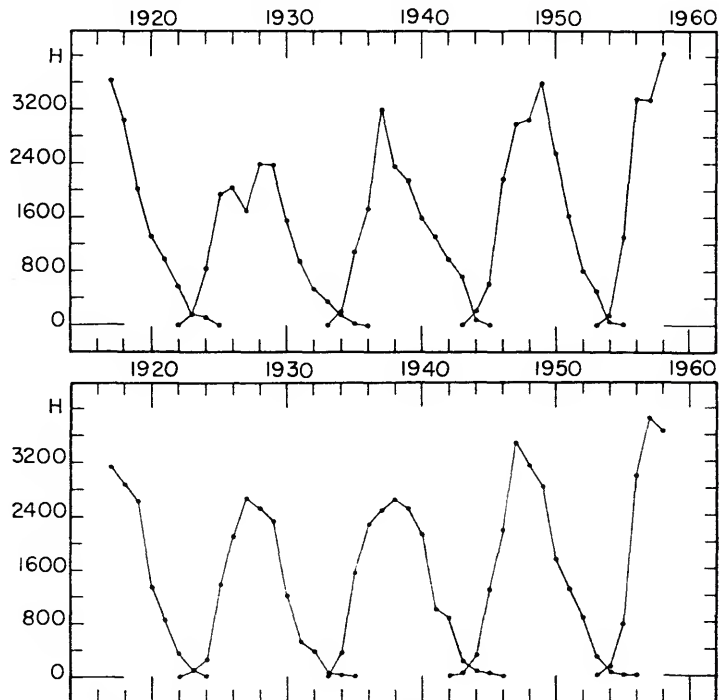


FIGURE 13.—Total number ( $N$ ) of sunspot groups per year in the northern (top) and southern hemispheres. Solid line, Mount Wilson data; open circles, Greenwich data.

FIGURE 14.—Total sunspot magnetic field intensity in the northern (top) and southern hemispheres observed at Mount Wilson per year, plotted in units of 100 gauss.



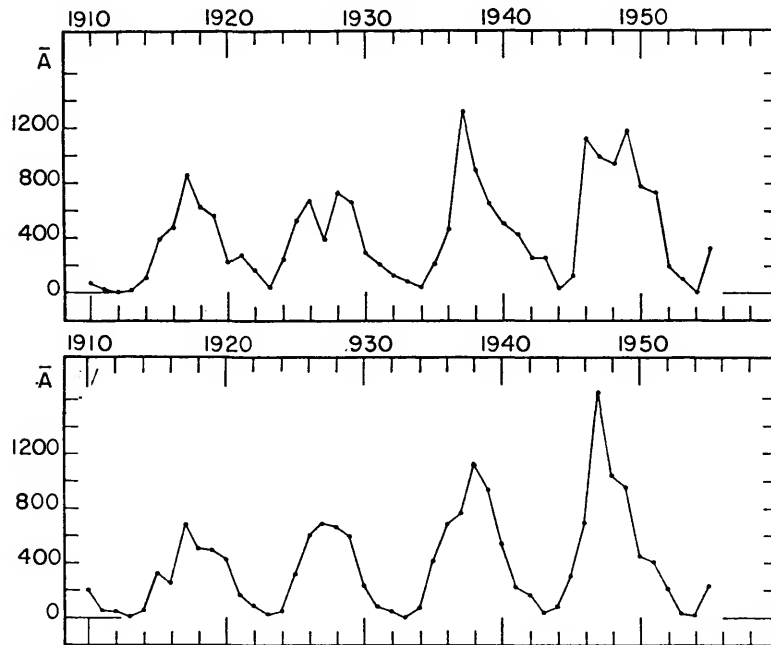


FIGURE 15.—Mean annual spotted area ( $\bar{A}$ ) (Greenwich, 1955) in the northern (top) and southern hemispheres.

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### Abstract

Published data on the magnetic field strengths and numbers of sunspots for the years 1917-1958 are used to study the structure of the sunspot zone as a function of heliographic latitude. Some evidence is presented in favor of the hypothesis that several zones of activity develop in each solar hemisphere, and that these zones remain stationary in latitude and are just sufficiently out of phase to simulate the latitude shift over the solar cycle described by Spoerer's law. A caterpillar diagram is proposed to supplement the well known butterfly diagram.