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On the Structure of the Sunspot Zone

By Barbara Bell

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
zones occur in each hemisphere, as proposed in the third concept listed above. The pattern for the 1947 cycle (fig. 2a) 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 Photographic 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° sums or 2° 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° 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-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Distribution with latitude on the sun of total magnetic field strength ($H$), plotted in 2° 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).}
\end{figure}
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b

c
Figure 2.—Distribution with latitude on the sun of total magnetic field strength ($H$), plotted in 2° running means and units of 100 gauss, of sunspots in cycles 18 and 19: a, No. 18 (1943-1954); b, No. 19 (1954-1958).
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FIGURE 3.—Distribution with latitude on the sun of total magnetic field strength ($H$), plotted in 2° running means and units of 100 gauss, of sunspots in cycles Nos. 15-19 (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° 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° sums (1+2°, 3+4°, etc.) were used. With even sums (2+3°, 4+5°, etc.), however, the fluctuations were barely significant, with $P>0.05$. The reason for this difference appears to be that the significance of the fluctuations arises primarily from the subsidiary peaks at

FIGURE 4.—Distribution with latitude on the sun of total magnetic field strength ($H$), plotted in 2° running means and units of 100 gauss, of sunspots for the period 1917-1958.
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 $1 \times 10^4$ for the northern and 1 in 500 for the southern hemisphere ($P \sim 10^{-8}$ and 0.005); and $P \sim 10^{-7}$ for north plus south. If the numbers for north and south are tested separately and each compared to its own smooth curve, one obtains $P \sim 10^{-9}$ for the north, $P \sim 0.5$ for the south, and $P \sim 10^{-8}$ 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 multizonality than do numbers of spot groups. The evidence from Mount Wilson numbers is
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° N and 17–18° 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 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° and 17–18°, 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
the apparent maxima of spot activity lie at
latitudes between the multiples of 5°, with
local minima approximately at the multiples
of 5°. In the north the principal maximum
lies at 12–13°, with a third secondary peak
clearly visible at 21–22°.

The subzones can be located also by study
of the 2° nonrunning sums. On a graph of
time against solar latitude, I plotted the lati-
titudes 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°. 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 de-
erived from the 2° 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° nonrun-
ning 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, fig-
ure 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 hemi-
sphere for the given sunspot cycle), per 5°
zone of latitude per year. The principal rea-
son 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, show-
ing 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
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°, 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),
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 concepts 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

The work reported in this paper has been supported by the Air Force Cambridge Research Center, Geophysics Research Directorate, through contracts AF19(604)-1394 and AF19(604)-4962 with Harvard University.
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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.
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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.