LONG TERM EVOLUTION OF SOLAR SECTOR STRUCTURE

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Abstract. The large-scale structure of the solar magnetic field during the past five sunspot cycles (representing by implication a much longer interval of time) has been investigated using the polarity (toward or away from the Sun) of the interplanetary magnetic field as inferred from polar geomagnetic observations. The polarity of the interplanetary magnetic field has previously been shown to be closely related to the polarity (into or out of the Sun) of the large-scale solar magnetic field. It appears that a solar structure with four sectors per rotation persisted through the past five sunspot cycles with a synodic rotation period near 27.0 days, and a small relative westward drift during the first half of each sunspot cycle and a relative eastward drift during the second half of each cycle. Superposed on this four-sector structure there is another structure with inward field polarity, a width in solar longitude of about 100° and a synodic rotation period of about 28 to 29 days. This 28.5 day structure is usually most prominent during a few years near sunspot maximum. Some preliminary comparisons of these observed solar structures with theoretical considerations are given.

The solar wind carries the magnetic field of the solar atmosphere to great distances out into the solar system, and provides a significant interplanetary magnetic field. Of all the solar wind parameters it seems that the imbedded magnetic field is the critical physical quality which governs the interaction between the solar wind and the magnetized Earth. Direct connection or linkage of interplanetary magnetic field lines and the terrestrial magnetic field provides for transfer of solar wind kinetic energy to the stretched out geomagnetic tail. The geomagnetospheric configuration appears to be dependent on the direction of the interplanetary magnetic field; and it was realized some years ago that the different configurations have different magnetic signatures as measured on the ground in the terrestrial polar caps (Svalgaard, 1968, 1972a; Mansurov, 1969; Wilcox, 1972). The important interaction parameter is the interplanetary electric field, $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$, in the frame of the magnetosphere, so that actually the components of the magnetic field $\mathbf{B}$ that are perpendicular to the solar wind velocity $\mathbf{V}$ are important. The ground-effects just mentioned allow one to determine the sign (and less reliably also the magnitude) of the azimuthal $\mathbf{B}$-component, BY, in the ecliptic plane (Friis-Christensen *et al.*, 1972; Svalgaard, 1973). Conceivably, the interactions are ordered in solar-magnetospheric coordinates rather than in solar-ecliptic coordinates but for our purpose the distinction between these two coordinate systems is not important. For a useful review of coordinate systems see Russell (1971).

Due to the spiral nature of the average interplanetary magnetic field with the field vector directed predominantly along an Archimedes spiral rooted in the Sun, there is normally a good correlation between the polarity (away from or towards the Sun along the spiral) and the sign of the azimuthal component BY. This correlation improves if the average properties are compared over progressively longer averaging intervals. As a result of all these considerations it follows that the large-scale features

of the sector structure of the interplanetary magnetic field (Wilcox, 1968) can be inferred reliably from high-latitude ground-based geomagnetic measurements. To the extent that the interplanetary magnetic field is rooted in the Sun (Severny *et al.*,1970; Scherrer, 1973), variations in the terrestrial magnetic field can be used as a diagnostic tool in exploring large-scale solar magnetic fields. This is particularly important since the geomagnetic field has been monitored for a much longer time than direct measurements of solar and interplanetary fields have been carried out. Svalgaard (1972b) inferred the interplanetary sector structure back to 1926 and suggested (Svalgaard, 1972c) that the time-evolution of the solar sector structure follows rather similar patterns in each sunspot cycle.

During most of the cycle a four-sector structure with a synodic recurrence period near 27 days is apparent. On the other hand, near sunspot maximum a superposed structure having polarity into the Sun and a width in longitude of about 100° and a recurrence period between 28 and 29 days can be observed. This $28\frac{1}{2}$ day feature coexists with the underlying basic four sectors for several years. It may at these times be more difficult to discern the four-sector structure clearly, and the observed solar-structure has in a first approximation only two sectors per rotation. But when the $28\frac{1}{2}$ day structure weakens sometime after sunspot maximum, the four-sector pattern becomes very prominent again as the cycle progresses towards sunspot minimum. The reason for this behavior and the interplay between the various structures and the solar cycle is generally not understood, and the very existence of the socalled 'sector-magnetism' (Wilcox, 1971) presents a puzzle to solar physics.

Some insights have recently been gained into the possible interaction between the solar sector structure and the polar fields of the sun (Svalgaard *et al.*, 1974; Hansen *et al.*, 1974; Howard and Koomen, 1974) and of the manifestation of the sector boundaries as arcade-type magnetic field configurations in the lower corona (Wilcox and Svalgaard, 1974). In these studies the existence of the sector structure has been taken as a starting point for the analysis, and no attempt was made to understand the fundamental nature and origin of the sector structure. Recent theoretical work by several researchers attacks the fundamental problems along different lines. Suess (1975) suggests that magnetic sectors are slow hydromagnetic waves controlled by the solar rotation, toroidal magnetic fields, and by stratification within the solar convection zone. Wolf (1974) considers long period oscillations involving the entire mass of the Sun, and constructs a theory of how these oscillations drive convective flows of global scale which then organize photospheric and coronal magnetic fields into sector patterns which rotate rigidly. Stix (1974) studied solutions of the solar magnetic dynamo equations which depend on longitude. Stix poinst out that the very same agents, namely non-uniform rotation and cyclonic turbulence, which could maintain the axisymmetric dipole field, also generate non-axisymmetric large scale fields which are rigid structures drifting in longitude without changing their shape. The rigidly rotating structures are then assumed to represent solar magnetic sectors. With only limited observational data on large scale solar fields it is difficult to guide the theory along realistic lines as well as to choose among the different models.

In this paper we present evidence for the notion that the basic four-sector structure is a manifestation of an intrinsic three-dimensional structure in the global solar magnetic and/or velocity fields. The structure is very long-lived and appears to have existed throughout the last five sunspot cycles, and by implication probably much longer than that. It will be shown that the sector boundaries drift slowly in longitude. These slow systematic longitude drifts are related to the sunspot cycle in the sense that from sunspot minimum until the polar fields reverse shortly after the maximum, the sectors drift westwards. After the polar field reversal, the sectors drift eastward until the next minimum, when they again resume a westward drift. The drifts are slow, of the order of 20° of longitude per year.

The inferred sector structure (Svalgaard, 1972b) has been analyzed with the goal of recognizing persistent patterns which may be present in this time series, and to study their possible evolution through the solar cycle. Almost five sunspot cycles are available for analysis. First we will present the inferred sector structure in a format which will allow the reader to identify the various features as described above and to evaluate the repeatability and significance of the data. Following this, we present a quantitative analysis aimed at removing subjective bias and substantiating the conclusions drawn from the material.

Since the inferred polarities actually refer to the azimuthal component BY of the interplanetary magnetic field (IMF), there are days ($\approx 10\%$) where the inferred polarity disagrees with the IMF sector polarity measured along the spiral because of fluctuations of the field. These days of disagreement tend to occur sporadically and the noise introduced by them may be decreased by suitable filtering of the data. Another source of noise is a bias by geomagnetic activity which is present in the inferred polarity list. Intervals of prolonged geomagnetic calm tend to cause the polarity to be inferred as away irrespective of the actual IMF polarity. This effect does not have large influence on larger scale features, as discussed by Svalgaard (1975).

We have assigned the value $+1$ to days with inferred away polarity and -1 to days with inferred toward polarity. Replacing the data by a 5-day running mean effectively filters out sporadic occurrences of days where the polarity and the azimuthal component has opposite sense, and tends to reduce the bias due to geomagnetic activity. In displaying the resulting data set a '$+$' is shown for each day with positive (away) smoothed polarity and a '$-$' is shown for each day with negative (toward) polarity. Figure 1 is an attempt to depict most of sunspot cycle number 16 of inferred sector structure in this way. Areas on the figure with predominant negative polarity have been outlined and stand out as 'islands' in a sea of positive polarity. There are two reasons why we have chosen to outline the negative polarity rather than the positive polarity. First, positive polarity seems to be more frequently observed near sunspot minimum (e.g. Wilcox, 1973), and second, the inferred polarities have a slight excess of positive polarity (55% away, 45% toward) partly because of the bias caused by geomagnetic activity. As a result negative polarity is more easily outlined. The reader is urged to examine Figure 1 critically and assess for himself to what degree the outlining reflects the structure formed by the negative polarity. The data is plotted two
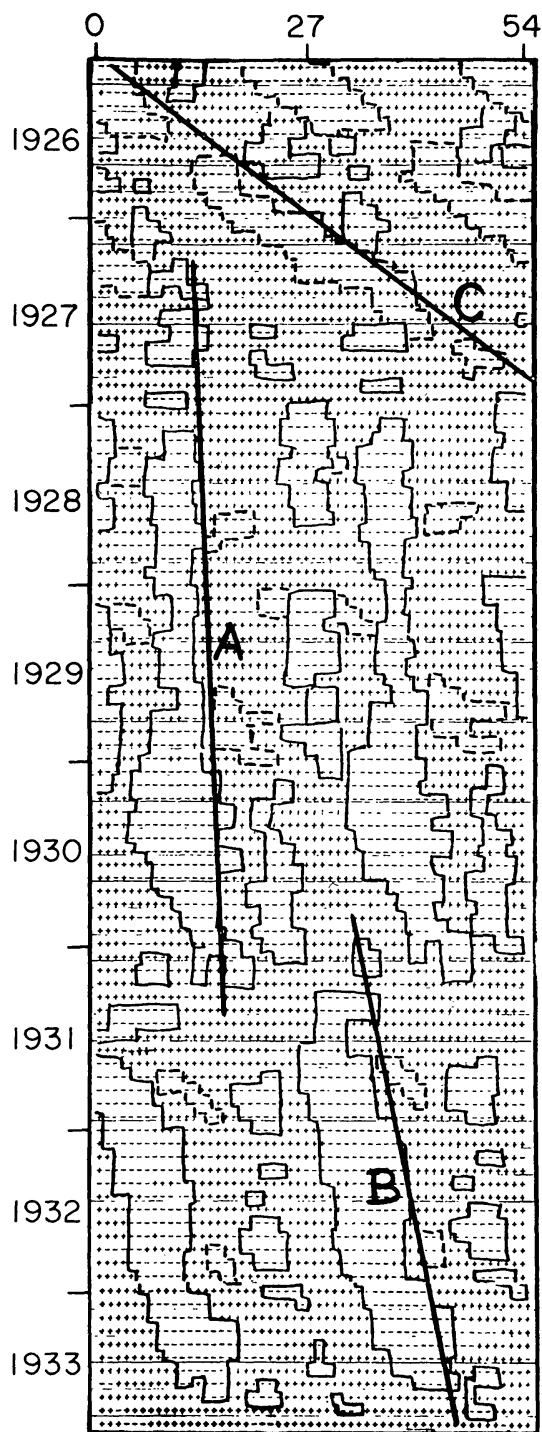
Fig. 1.　Display of the inferred polarity of the interplanetary magnetic field during sunspot cycle number 16. Two successive rotations are displayed horizontally in order that the largescale structures can be more readily perceived. A day with inferred field polarity away from the Sun is represented with a + sign, and a toward day is represented with a − sign. A five day running mean has been applied to the original data set. The field structures A, B and C are described in the text. The synodic calendar period of this display is 26.84 days.

rotations side by side down through the sunspot cycle. For reasons to become clear later the synodic rotation period was set to 26.84 days rather than the Bartels period of 27 days or the Carrington period of 27.275 days.

At first we will draw attention to the very stable negative structure having its rightmost boundary marked by the line 'A' on Figure 1. This structure is immediately discernible during the four years 1927–30. It has a recurrence period very close to 26.84 days because it runs almost vertically down in the figure. Since two rotations are shown side by side, the structure just mentioned can of course also be seen to the right of line 'A'. Between these two manifestations of the same structure a somewhat more weakly defined but similar negative structure can be found. Thus we infer that during the interval 1927–30 a clear four-sector structure existed, and that it had a recurrence period close to 26.84 days.

Next we will focus on the negative sector having its boundary marked by 'B' on Figure 1. This structure is prominent during 1931–33 and has a recurrence period somewhat longer than 26.84 days, because of the slant down to right in the figure. In the course of 3 years, or of 40 rotations, the boundary marked 'B' is delayed 12 days compared to a 26.84 day recurrence line which would run vertically down. Therefore, the recurrence period of the 'B'-line is $26.84 + 12/40 = 27.14$ days. Again, because two rotations are shown side by side, the B-structure can of course also be seen in the left side of Figure 1. Between these two manifestations of the same structure a more weakly defined negative sector can be seen as a sequence of negative 'islands'. Thus we infer that during the interval 1931–33 a four-sector structure existed, and that it had a recurrence period close to 27.14 days.

Finally, during the interval 1926–27 the structures seem to be strongly inclined, indicating that the recurrence period is substantially larger than 26.84 days, in fact about 28.9 days. These structures are identified by the line marked 'C' on Figure 1 being near to the boundary between a negative sector and the following positive sector. This negative sector has been outlined with a stippled line to set it apart from the other structures having recurrence periods near 27 days. The 'A'-structure discussed above may be followed up through 1926–27 illustrating the coexistence of 27-day and 29-day structures. Also, during the time when the A and B structures are clearly delineated some areas of negative polarity can be seen, which are not obvious parts of the 27-day systems. These areas have been outlined with stippled lines and seem to exhibit a ≈ 29 day recurrence just as the C-structure. Recognizing the change in recurrence period that occurs in late 1930, we may follow the A-structure as it continues into the B-structure or, stated differently, regard the A- and the B-structures as the same four-sector structure that just displayed a change in recurrence period. These somewhat subjective statements will be substantiated later by quantitative analysis.

To recognize patterns such as the ones described above in the inferred sector structure a quantitative method of analysis using a test function may be employed. The test function is a short time series which defines the pattern we are looking for. The cross correlation coefficient between the test function and the observed time series –

or a subset of this – is a measure of how strongly the pattern is present in the observed data provided that the phase difference between the pattern in the test function and the corresponding pattern in the observations is zero. By introducing time lags between the test function and the observed time series we can calculate cross-correlation coefficients for various lags and determine the lag at which the magnitude of the correlation is highest. This lag then defines the phase shift between corresponding patterns in the two series.

In the present analysis a test function was constructed to define a four-sector structure with a recurrence period of 27 days. The test function included 37 successive 27-day intervals each consisting of 7 days of negative polarity (represented by -1) followed by 7 days of positive polarity (represented by $+1$) and then finally 7 days of (-1) and 6 days of $(+1)$. This idealized pattern – constituting a time series of 1009 points – sometimes had a rather high resemblance with 1009 day subsets of the time series of inferred polarities; the cross-correlation coefficient reaching a magnitude of 0.6. More typically the correlation was of the order of 0.25. The expected cross correlation coefficient between the test function and 1009 random values would not exceed 0.03. Even allowing for the high positive conservation in the data we should not expect a cross-correlation coefficient exceeding 0.07. Consequently we conclude (as is already evident from simple visual inspection of the inferred polarity series, e.g. Figure 1) that a four-sector structure is an easily recognizable pattern in the inferred sector polarity tabulation.

Since we in general do not know the phase relation (if any) between our test function and the polarity series, cross-correlation coefficients were calculated for lags varying between 0 and 27 days. An example is shown in Figure 2 where the test function was centered on Bartels rotation number 1783, that is the 19th 27-day interval of the test function corresponded to rotation 1783 for a lag of 0 days. A lag of 1 means
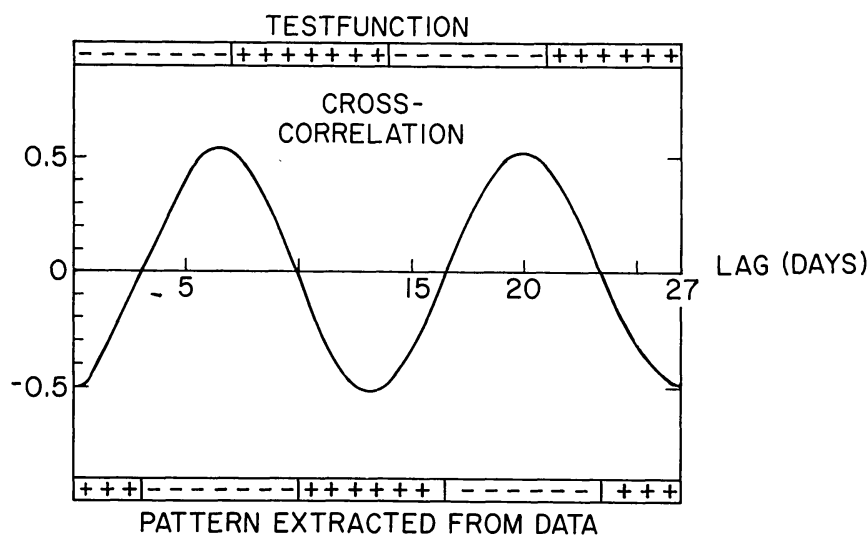

Fig. 2.   A test function representing a four-sector structure (top of figure) is compared with the time sequence of inferred interplanetary magnetic field polarities. The resulting cross-correlation as a function of lag is shown in the middle of the figure, and a pattern extracted from the original data by this means is displayed at the bottom of the figure. Further details of the method are given in the text.

that the test function has been displaced by 1 day in time, so that the first day of the 19th 27-day interval corresponds to the *second* day of rotation 1783, etc. The test function itself is shown in symbolic form at the top of the figure. In the lower part of the Figure is shown a pattern which would produce high cross-correlation with the test function at a lag of 3 days.

This somewhat painstaking explanation of the basic method of the analysis should satisfy the reader that it is a straightforward procedure to obtain the phase difference (3 days in the above example) between the inferred sectors and the idealized test function. It is found that this phase difference changes slowly with time. The changes are of the order of 1–2 days or 10°–30° of solar longitude per year. It is implied above that the test function is compared to a subset of the inferred polarities varying the lag from 0–27 days. The phase difference is now determined as in the example above. Another subset is then selected by moving the starting day of the set an *integral number* of 27-day intervals forwards in time. The phase difference can then be determined again, etc.

In view of the rate of the phase change, the subsets were spaced exactly 6 Bartels rotations (6×27 days) apart and the phase difference and maximal magnitude of the cross-correlations were determined using lags varying from 0 to 27 days. The resulting values of phase and magnitude are ascribed to the epoch of the Bartels rotation which was compared to the central (19th) rotation of the test function. The phase information can be thought of as referring to the phase of the four-sector structure relative to a fiducial 27-day calendar. It appears that a four-sector structure can be recognized most of the time as an underlying pattern, and that this pattern shows significant and reproducible changes in each sunspot cycle.

The choice of 37 rotations as the length of the test function is dictated by the desire to filter out short-term fluctuations by having a long enough test function and at the same time to minimize the influence of the 28–29 day feature. The ~ 1.5 day difference in recurrence period between the $28\frac{1}{2}$ day feature and the 27 day periodic four-sector pattern will in the course of ± 18 rotations amount to just 27 days, so that the influence of the 28–29 day feature is felt at all phases within the 27-day interval and therefore tends to cancel out when a test function of 37 rotations ($\sim 2 \times 18$) is used.

The result of the above procedure is shown in Figure 3. The points where the cross correlation coefficient, as a function of lag, changes sign have been marked for each central rotation to show the evolutionary changes of the phase difference between the 27-day calendar and the sector structure. Usually the phase changes only slightly in the course of the six rotations between the beginning of each 37 rotation subset of the observed data. This justifies most of the connections between the crosscorrelation phases of successive subsets we have indicated in the figure by a continuous and a broken line. In a few cases when the phase changes rapidly, the resulting ambiguities have been resolved as shown on the Figure. We note here the possibility that the ambiguities could perhaps have been resolved differently, but we will contend that the choices made in Figure 3 lead to a consistent, repeating large-scale pattern, and we will explore some of the implications of this pattern.

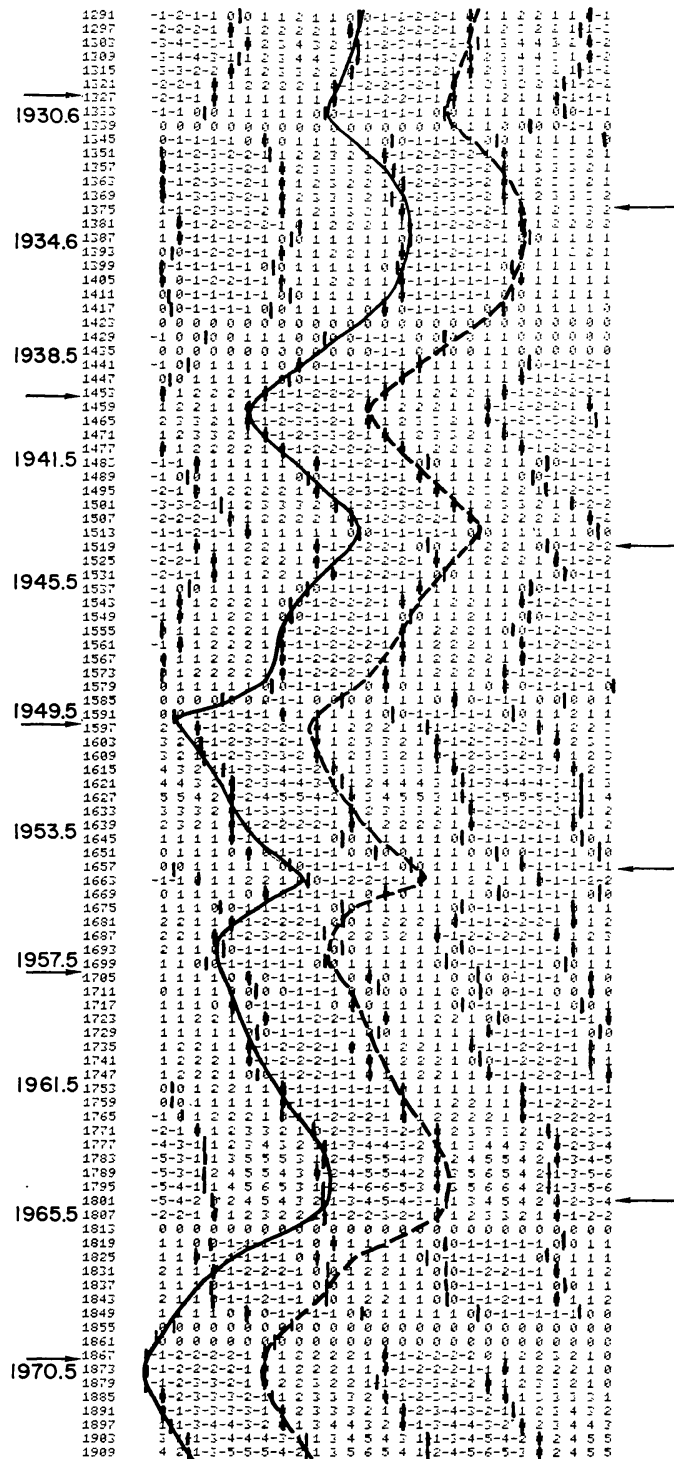468 LEIF SVALGAARD AND JOHN M. WILCOX

Fig. 3. The results of the test pattern analysis shown in Figure 2 are displayed during the last five sunspot cycles. Selected 27-day solar rotations are displayed (see text for further details). A day on which the cross-correlation analysis shown in Figure 2 yielded a cross correlation between −0.15 and −0.25 is represented in this figure by a −2, and the other ranges of cross-correlation are represented in an analogous manner. Note that in this figure a + sign indicates intervals (phases) in which the test pattern and the inferred field data have a positive correlation. A four-sector pattern is apparent in this display, and the boundaries of one persistent interval having negative cross correlation are displayed with a solid and a dashed line. The times of sunspot minima are indicated with arrows on the right of the figure, and the times near which the solar polar field changed polarity are indicated with arrows on the left. Note that the fiducial calendar period in this figure is 27.0 days.

The continuous line on Figure 3 marks the phase of a $(-,+)$ sector boundary relative to the fiducial 27-day Bartels calendar. At a $(-,+)$ boundary the polarity changes from $-$(inward) to $+$(outward). This line is shown separately on Figure 4 where we also have indicated the times of sunspot minima and the probable times of polar field reversals for sunspot cycles 16 through 20. The polar field reversals have only been directly observed twice (Babcock, 1959; Howard, 1974), namely in 1958 and recently
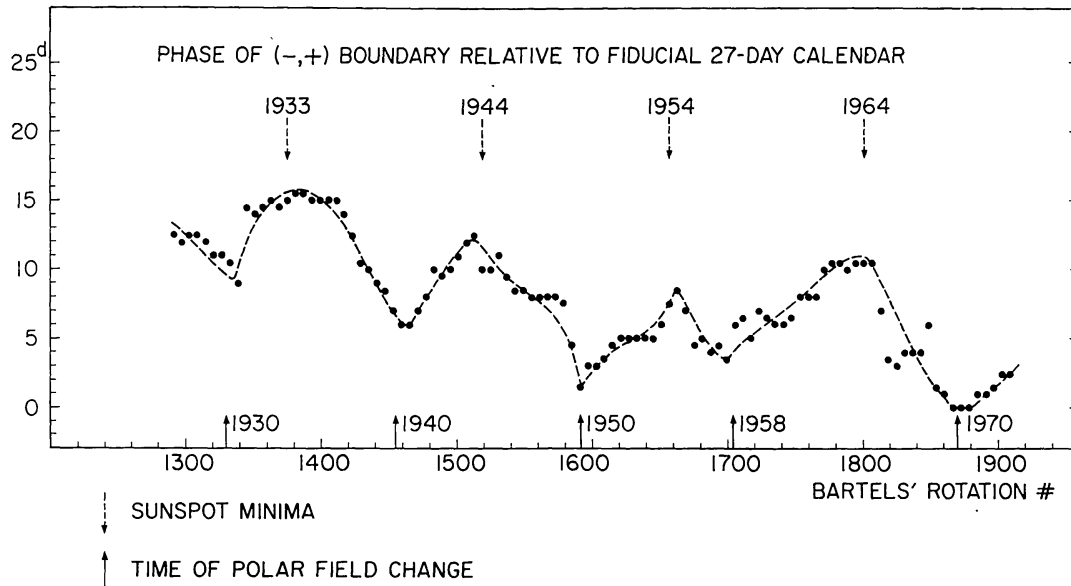

Fig. 4. The positions (phases) of the boundary indicated with a solid line in Figure 3 are plotted as a function of time during the last five sunspot cycles. The dashed arrows at the top of the figure indicate the times of sunspot minima, and the solid arrows at the bottom of the figure indicate the times near which the polarity of the solar polar fields changed. This figure shows a tendency for the four-sector pattern to drift westward during the first half of the sunspot cycle and to drift eastward during the second half of the cycle.

in 1970. However, analysis of an annual variation of the predominant polarity of the interplanetary field near the Earth (Rosenberg and Coleman, 1969; Wilcox and Scherrer, 1972) and also poleward movements of the prominence zones (Waldmeier, 1973) suggest that on the average the polar fields may reverse 2–3 years after sunspot maximum. The inferred times of polar field changes are indicated by solid arrows in the lower part of Figure 4.

Systematic trends in the change of phase are apparent in Figure 4. It appears that the phase difference is generally decreasing in the interval from sunspot minimum to the time of polar field reversal; and that the phase difference is generally increasing from the time of polar field reversal to next sunspot minimum. A decreasing phase difference between the inferred sector structure and the 27-day test function indicates that the recurrence period of the sector structure is less than 27 days, while an increasing phase difference is indicative of a recurrence period longer than 27 days. The average phase change for the decrease is -0.14 days per 27 day rotation corresponding to a synodic recurrence period of 26.86 days. The average change for the phase in-

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crease is +0.10 days per rotation corresponding to a recurrence period of 27.10 days.

The preceding analysis seems to indicate that the properties of the four-sector structure vary the same way in each sunspot cycle. In our discussion of Figure 1 – referring to cycle 16 – we noted the apparent change of recurrence period around 1930, and we conclude that similar changes have also taken place in the four other cycles covered by our data. Furthermore, there seems to be a change of recurrence period at each sunspot minimum. If the average recurrence period is near 27.0 days we can express our finding in this way: in the beginning of the sunspot cycle the four-sector structure rotates slightly faster, while it rotates slightly slower in the later part of the cycle. This is equivalent to a westward drift during the first half of the cycle, followed by an eastward drift of the structure during the second half of the sunspot cycle.

The conclusion that the sector structure displays repeatable patterns in each sunspot cycle is further substantiated in Figure 5. Here, the five cycles are plotted side by side with the sector structure indicated in basically the same way as in Figure 1. In addition, negative sectors are shown in black, and the $28\frac{1}{2}$ day feature is shown with shading. At times when the two sectors overlap, they have been resolved in an arbitrary way.

INFERRED SOLAR MAGNETIC SECTOR STRUCTURE DURING FIVE SUNSPOT CYCLES

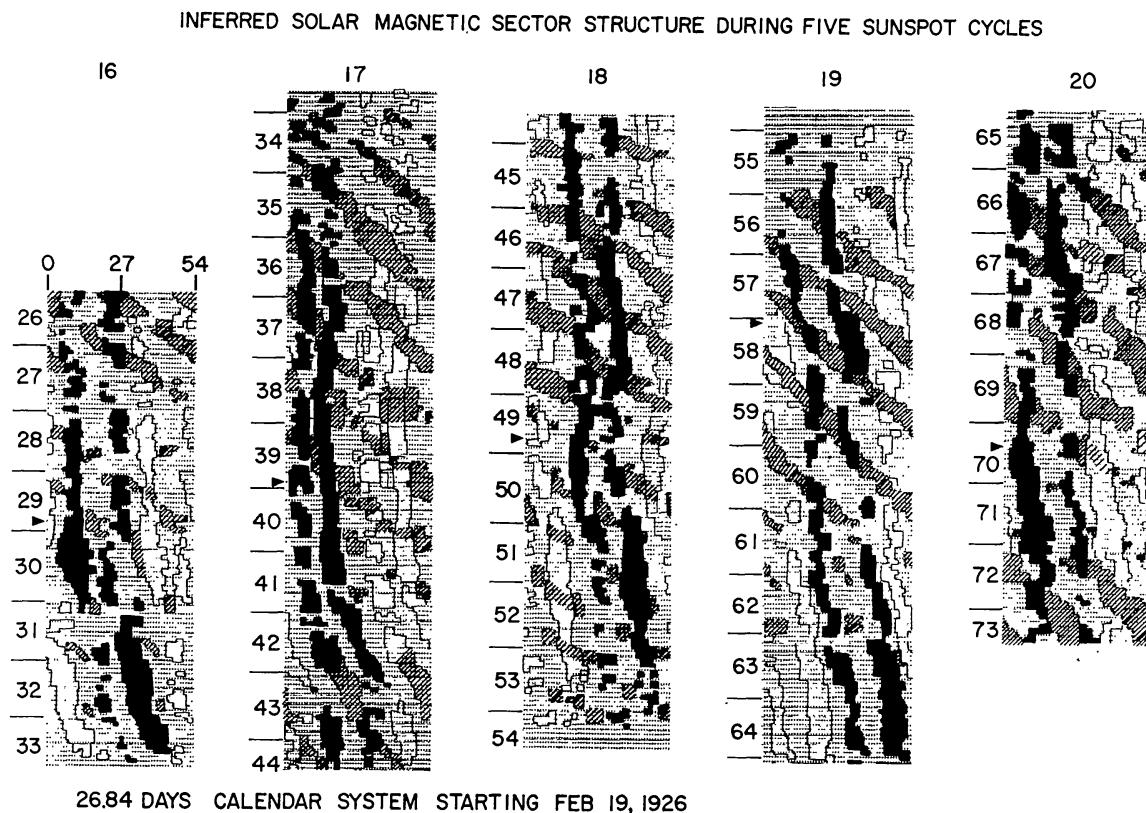26.84 DAYS CALENDAR SYSTEM STARTING FEB 19, 1926

Fig. 5. A plot of the inferred solar magnetic structure during sunspot cycles 16–20. A 26.84 day calendar system starting February 19th, 1926 is used. Two successive rotations are displayed horizontally to aid in pattern recognition. Sectors with field polarity toward the Sun are shaded black if they are judged to be part of the four-sector pattern, and have a dashed shading if they are judged to be part of the 28.5 day structure. A visual impression of the large-scale solar magnetic features described and analyzed in the text can be obtained from this figure.

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As in Figure 1, two rotations are shown side by side; in one of these rotations the 27-day structure has been emphasized while in the other rotation, the $28\frac{1}{2}$ day structure has been emphasized. Again, we note that a certain element of subjectiveness is unavoidable, but it seems certain that the large-scale structure is not affected by the exact way in which the features are outlined in the subjective analysis. Figure 5 shows in a compact representation the three principal features that emerge from the present analysis: (i) a persistent four-sector structure which may be followed from one cycle to the next and presumably represents a very long-lived structure in solar magnetic fields, (ii) systematic changes of the recurrence period – or rotation period – of this four-sector structure: faster rotation in the first half of a sunspot cycle, slower rotation in the last half, and (iii) the existence of a negative polarity feature with a $28\frac{1}{2}$ day recurrence period; the $28\frac{1}{2}$ day structure seems to be most prominent near sunspot maximum, although it at times can be quite distinct even near minimum such as in 1943 and in 1972–73.

At this point it is appropriate to discuss the semantics of the phrase: 'persistent long-lived structure'. A structure may exist as a physical entity for a certain time and then decay or disappear. A similar but not identical structure may appear shortly after the disappearance of the first structure. By 'not identical' we imply that the physical process which creates the new structure can operate without reference to or 'memory' of the first structure. We are trying to make a distinction between a 'new' structure and an intensification of a pre-existing structure which for some time had weakened to below detectability. We realize that this distinction cannot always be made and that the concepts 'existence' and 'identity 'may ultimately be defined operationally. From Figure 5 it seems that the negative sectors shown in black display a continuity in phase such as to suggest that we are seeing the same structure – at times waxing and waning – through all five sunspot cycles. It cannot be ruled out that the sector structure may only be stable for a few years at a time, and as one pattern decays, a new one emerges to replace it. The new structure then – for some reason – seems to appear at nearly the same phase in the 27-day calendar system as the previous structure had. It is not clear that this alternative interpretation is significantly distinct from the simpler point of view that we are just observing the same basic structure throughout the entire period from 1926 to 1973. Most researchers would agree that it is difficult to understand how solar magnetic structures can persist for a period of this length, but it is also difficult to understand how the structures can exist for even two or three years. These difficulties arise when solar magnetic fields are considered to be basically surface phenomena which are rapidly being destructured by differential rotation and supergranular motions. The existence and persistence of a solar sector structure as discussed in this paper may suggest that the magnetic field itself or perhaps velocity fields – which may play a role in structuring the magnetic field – are fundamental features of the Sun rather than superficial perturbations of the 'quiet Sun'.

A characteristic feature of the widely accepted Babcock-Leighton model of solar magnetic fields and of the solar cycle (Babcock, 1961; Leighton, 1969) is the conversion of a poloidal magnetic field to a toroidal field and back again to a poloidal field of

opposite polarity. In this process – which furthermore relies on small-scale activity to work – hardly any information about a structured magnetic feature can be transmitted from one cycle to the next, to say nothing about five cycles. The stability of the four-sector structure suggested in this paper would imply that at least part of the magnetic fields on the Sun does not engage in the Babcock-Leighton process. The systematic change of rotation period during a sunspot cycle may on the other hand indicate that the sector structure is coupled in some way to the sunspot cycle.

The rotation period may be investigated in more detail with an auto-correlation analysis. The inferred sector data has been divided into two subsets. One includes data from sunspot minimum to the inferred time of polar field reversal, and the other in-cludes data in the interval from the reversal to the next minimum. This division corre-
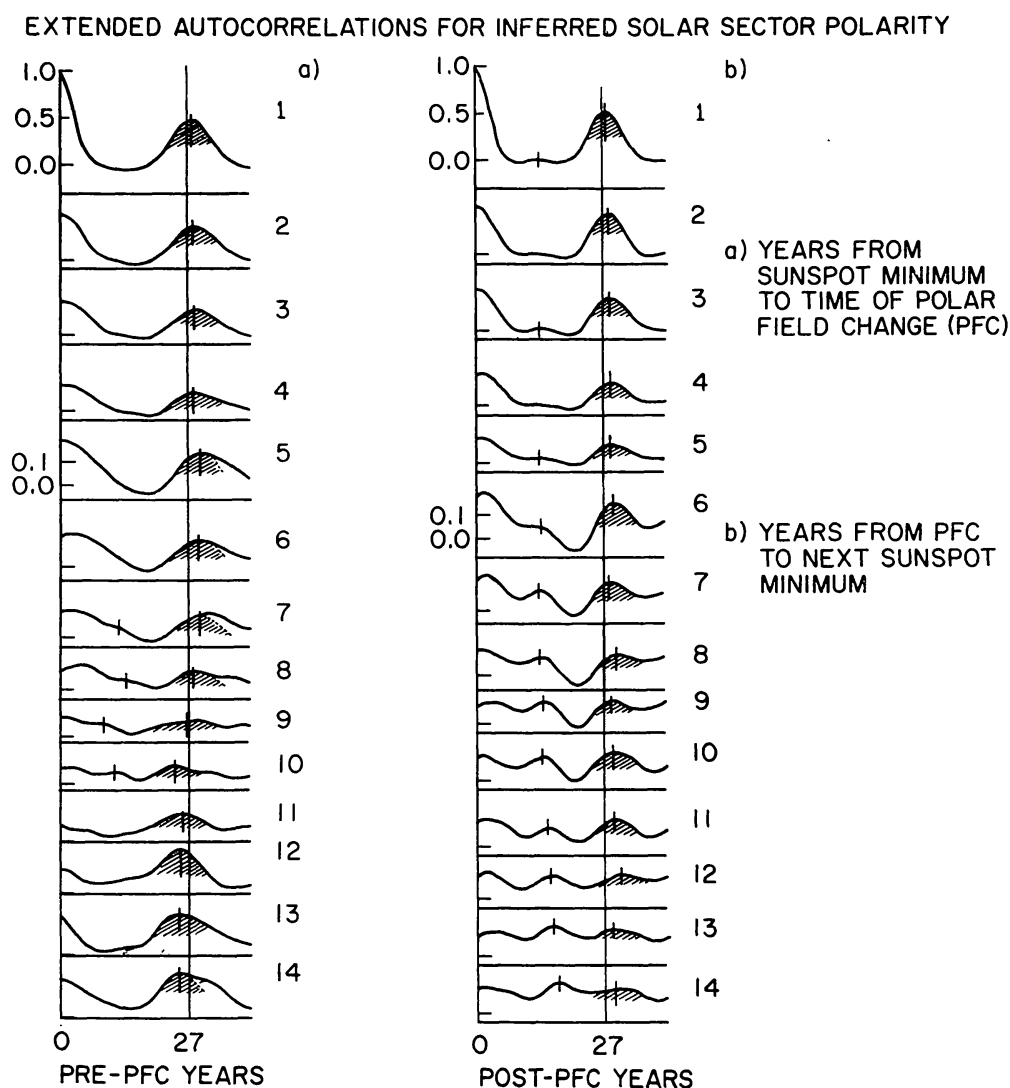

Fig. 6. Recurrent peaks in the extended auto correlations of the inferred solar sector polarity are shown for the cases of (a), years from sunspot minimum to the time of change of solar polar field polarity, and (b), years from polar field change to the next sunspot minimum. The rotation period associated with each recurring peak is indicated by a small vertical line. Note that for the later recurrences (beyond about 10) the two data sets display a systematic difference.

sponds roughly to the first and the second halves of a sunspot cycle. For each subset the auto-correlation function was computed out to a lag of three years. Recognizable peaks were present in both auto-correlation functions for lags up to about a year. After that it became increasingly more difficult to distinguish clear peaks over the noise. The dominating characteristic of these auto-correlation functions is a series of peaks spaced at approximately 27 day intervals. Following the reasoning in Wilcox *et al.* (1970), the peak near $n \times 27$ days is caused by the nth recurrence of features having a life time greater or equal to $n \times 27$ days. Features with a shorter life time cannot contribute to this peak.

Let τ_n be the lag at which the nth peak maximizes; we may then assert that the recurrence period for features recurring n or more times is $P_n = \tau_n/n$. If P_n is independent of n, the physical interpretation of the auto-correlation curve is straightforward. The recurring peaks are shown in Figure 6 where successive 27 day segments of the auto-correlation functions have been placed vertically below each other to emphasize the recurrence property and to facilitate comparison of the recurrence periods or more strictly the peak times τ_n. Up to recurrence number 7 or 8 there is no significant
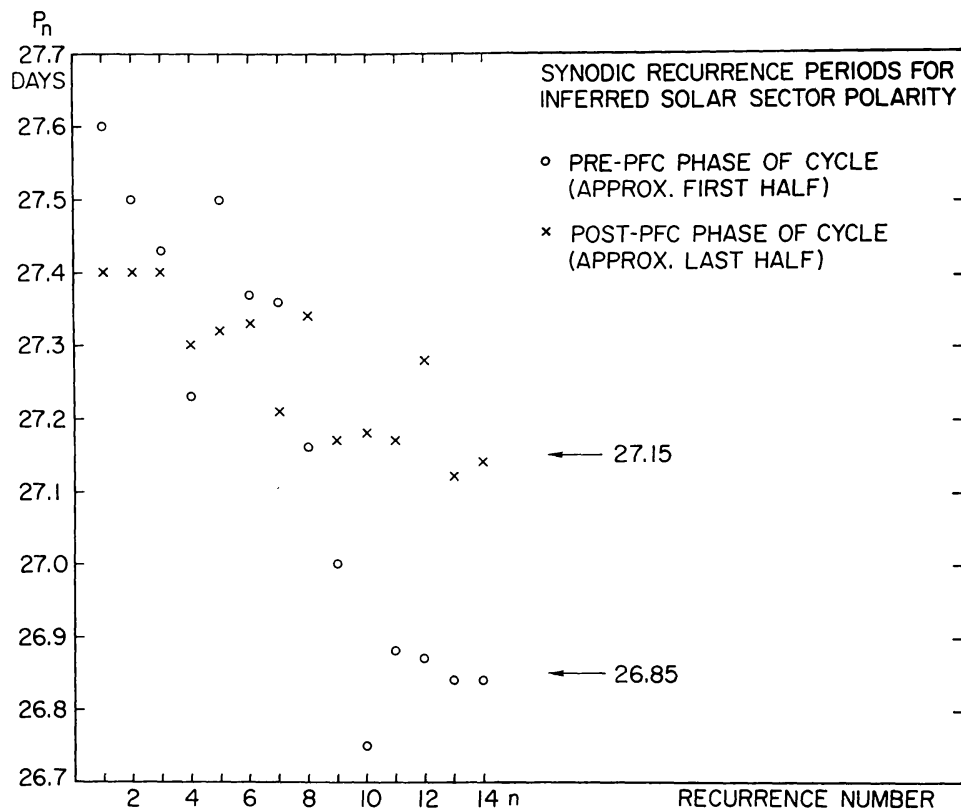

Fig. 7.   Synodic recurrence period of the inferred interplanetary field polarity as a function of recurrence number (see text). The recurrence period corresponding to each of the peaks shown in Figure 6 is plotted as a function of recurrence number. For the field polarities corresponding to the first half of the sunspot cycle the peaks corresponding to recurrence number greater than 10 cluster about 26.85 days, while for the second half of the cycle the corresponding peaks cluster about 27.15 days. This gives quantitative evidence for a westward drift of the sector pattern during the first half of the sunspot cycle, and for an eastward drift during the second half of the cycle.

difference between the two subsets; but from about peak number 8, there seems to be a tendency for the auto-correlation function to peak earlier during the first half of the sunspot cycle than during the second half. Recurrence peak number 11, for example, falls at a lag lesser than 11×27 days for the first subset, and at a lag greater than 11×27 days for the second set. In Figure 7 we have plotted the recurrence period $P_n = \tau_n/n$ as function of n for the two phases of the sunspot cycle. As n increases from 1 to 8, P_n decreases in both cases from 27.5 to 27.2 days. As n increases further to 14, P_n only decreases to about 27.15 days for the second subset referring to the time from polar field reversal to sunspot minimum. In contrast, P_n decreases to about 26.85 days for the first data set, corresponding to data from sunspot minimum until a few years after sunspot maximum when the polar field reversals are postulated. Thus the auto-correlation analysis is consistent with our previous conclusions about the sunspot cycle changes in recurrence period of the solar sector structure.

A difficulty arises in the interpretation of the analysis because P_n is not constant for $n < 8$. The same phenomenon is also seen in auto-correlation analyses of the photospheric magnetic field (Wilcox and Howard, 1970) and of the green line coronal emission (Antonucci and Svalgaard, 1974). A possible explanation may be that active regions modify the sector structure to the extent that the recurrence properties of the sectors to some degree also reflect recurrence properties of active regions. This modification is then observed to become less and less prominent with increasing time-lag, until it finally disappears for $n \approx 8$, corresponding to the maximum life time of active regions.

A detailed comparison of these observations with the theoretical considerations mentioned above is reserved for a future paper; however, we make a few preliminary comments. Using linear kinematic dynamo theory, Stix (1974) finds non-axisymmetric modes that are rigid structures drifting in longitude. Solar sector boundaries can therefore live much longer than the surface differential rotation would allow for a frozen-in field. Both eastward and westward propagating modes exist, and for reasonable values of solar parameters Stix finds for a four-sector structure a drift rate of about 27° of longitude per year for the westward mode, and about 8° of longitude per year for the eastward mode. It is tempting to identify these modes with the observations shown in Figure 4, in which the foursector structure drifts westward from sunspot minimum to the time of change of polarity of the solar polar fields (approximately the first half of the sunspot cycle), and then drifts eastward during the second half of the cycle. The observed drift rates are comparable (within a factor of about 2) with the theoretical drift rates.

The theory predicts that westward modes have a considerably larger drift rate than do eastward modes. Our analysis yields the *relative* westward and eastward drifts, but does not yield an *absolute* drift rate with which to compare them. We therefore can not yet investigate this aspect of the theory. It appears very likely that the period of the four-sector structure is within a very few hundredths of a day of 27 days. If so, Bartels (1934) was fortunate in his choice of the 27-day calendar for representing geomagnetic activity.

The observation that the westward mode exists during the first half of the sunspot cycle and the eastward mode during the second half should be investigated within the framework of this theory.

A few possible relations between theory and observation are described above. We may anticipate many more comparisons with the several theories (including those cited earlier) that may be relevant.

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