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# PHOTOSPHERIC MAGNETIC FIELD ROTATION: RIGID AND DIFFERENTIAL

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**Abstract.** An autocorrelation of the direction of the large-scale photospheric magnetic field observed during 1959–1967 has yielded evidence that the field structure at some heliographic latitudes can display both differential rotation and rigid rotation properties.

Comparisons of the observed interplanetary magnetic field with the observed photospheric magnetic field have disclosed a solar sector structure in the weak large-scale photospheric magnetic field (Wilcox and Howard, 1968; Schatten *et al.*, 1969; Wilcox *et al.*, 1969). A boundary of the solar sector structure is shown in Figure 1 (after Wilcox *et al.*, 1969). On the east side of the boundary the weak background photospheric magnetic field is predominantly out of the sun in equatorial latitudes on both sides of the equator, over a range from approximately 40°N–40°S. On the westward

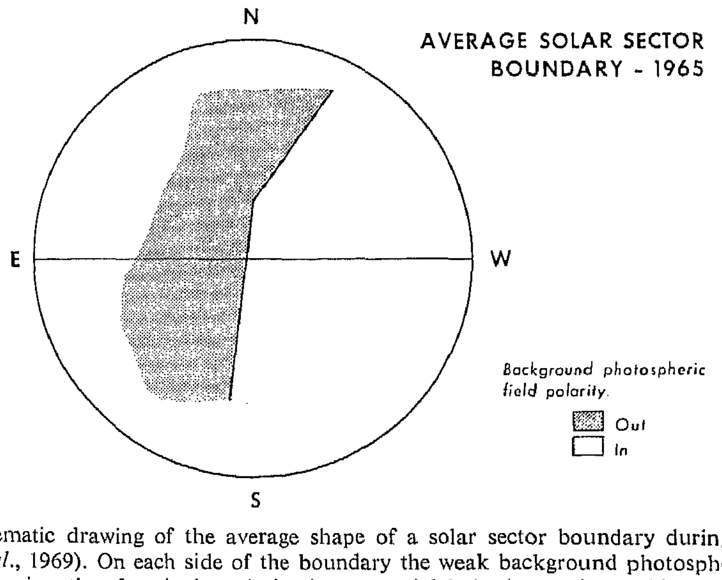


Fig. 1. Schematic drawing of the average shape of a solar sector boundary during 1965 (after Schatten *et al.*, 1969). On each side of the boundary the weak background photospheric magnetic field is predominantly of a single polarity in equatorial latitudes on both sides of the equator.

 

side of the boundary the predominant polarity is into the sun. The solar sector boundaries appear to rotate with the sun in an almost rigidly rotating system, in the sense that the deviations of a boundary from a straight line in the north-south direction are small compared to the shearing effects to be expected from differential rotation. The solar sector structure differs from the classical Babcock (1961) picture of solar magnetism in two fundamental respects: (1) The solar sector structure has little or no differential rotation, while the Babcock model utilizes the stretching effects of differential rotation to amplify an assumed poloidal magnetic field and thus ultimately produce bipolar magnetic regions and solar activity; and (2) the solar sector structure has the same polarity north and south of the equator, while as a natural result of the field amplification by stretching caused by differential rotation, the Babcock model leads to opposite polarities in the northern and southern hemispheres for the preceding sunspots and portions of bipolar regions. The Babcock model discusses localized bipolar active regions in the latitude range of solar activity, and polar fields of a single predominant polarity. The solar sector structure deals with large-scale regions of a predominant polarity having a width in longitude of approximately 100° and extending throughout the latitudes of solar activity.

A recent investigation (Wilcox and Howard, 1970) has shown that the large-scale photospheric magnetic field observed with the solar magnetograph has a differential rotation not greatly different from that observed for recurrent sunspots by Newton and Nunn (1951). It thus appears that the photospheric field simultaneously displays both differential rotation and rigid rotation. The solar sector structure is a property of the sun, yet it has been investigated only by comparisons of observed interplanetary fields with observed photospheric fields. It would be desirable to investigate the solar sector structure using only solar observations. The problem in this case is one of signal-to-noise. The solar sector structure appears to exist with an average field magnitude comparable to the minimum field that can be detected with a solar magnetograph. Furthermore, solar features such as bipolar magnetic regions are clearly exceptions to the solar sector structure and will appear as a kind of 'noise' in investigations of this structure. The interplanetary sector structure appears very clearly (with a very small noise content) in the observations of the interplanetary magnetic field. Thus an investigation of solar sector structure using comparisons of interplanetary and solar magnetic fields involves an interplanetary signal with very little noise and a solar observation with a much larger 'noise' content. If the solar sector structure is investigated using only solar observations then only a signal with a large 'noise' content is available.

One method in such a situation is to use a large number of observations to improve the signal-to-noise ratio. In the work of Wilcox and Howard (1970) observations over an interval of six months were used for each individual analysis. In the present investigation observations obtained with the solar magnetograph at Mount Wilson Observatory over an interval of eight years (1959–1967) are used (for details of the observations see Wilcox and Howard (1970)). Figure 2 is a schematic of the method. The basic unit of observation employed here is the predominant direction of the photospheric magnetic field over a range of about 3° in latitude and about $6\frac{1}{2}°$ of longitude (the latter corresponding to solar rotation in 12 h). Each observation is recorded when this element of solar area is at central meridian. Thus for a given solar latitude we have a time series giving the predominant direction of the field in units of 12 h, with the time series extending over 8 yr. For a time series of this length an autocorrelation can be computed with a range of lags from 0 to $1\frac{1}{2}$ yr without serious loss of statistical significance. Such an extended autocorrelation is schematically represented in the top curve of Figure 2. The $n$th recurrent maximum is at a lag of $n\tau_n$. (The

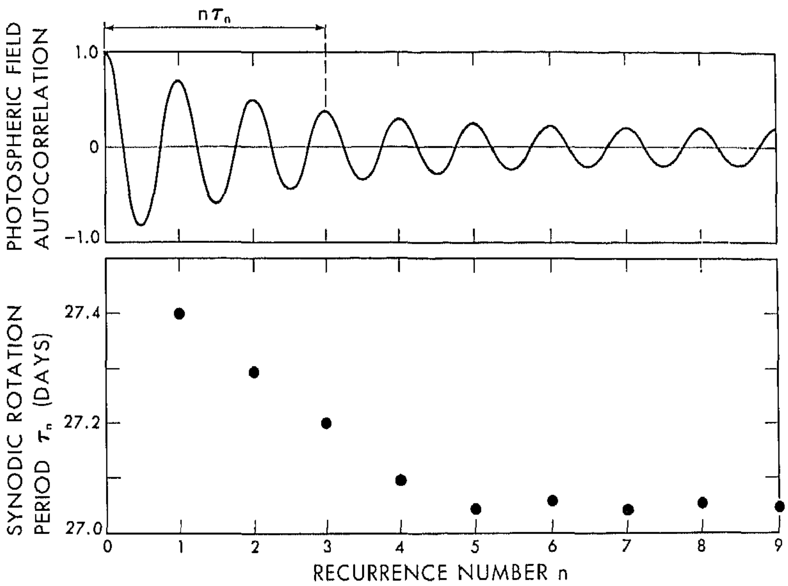


Fig. 2. Schematic drawing of the extended autocorrelation method used in this investigation. A synodic rotation period $\tau_n$ is associated with the lag $n\tau_n$ of a peak in the autocorrelation.

lag corresponding to each peak is calculated using the position of the centroid.) A synodic rotation period $\tau_n$ can then be associated with the $n$th peak, as indicated in the lower portion of Figure 2. Solar features with a lifetime of a few solar rotations (e.g. bipolar regions) will dominate the first few values of the recurrence number $n$, but will have little effect on peaks for $n > 10$ since only solar features whose lifetimes are roughly a year or more can contribute to the analysis for $n > 10$. Thus we expect the shearing effect of differential rotation on comparatively short-lived features to dominate the small values of recurrence number $n$, while a possible rigidly rotating solar sector structure observed with a low signal-to-noise ratio might nevertheless be discernible at the larger values of recurrence number after the large magnitude effects of the shorter-lived active regions no longer predominate.

We will discuss first the results obtained for the northern hemisphere. Figure 3 shows the autocorrelations obtained at latitudes 40°N–0°. The recurrent peaks selected for further analysis are shaded in this figure. Nearly always these peaks have

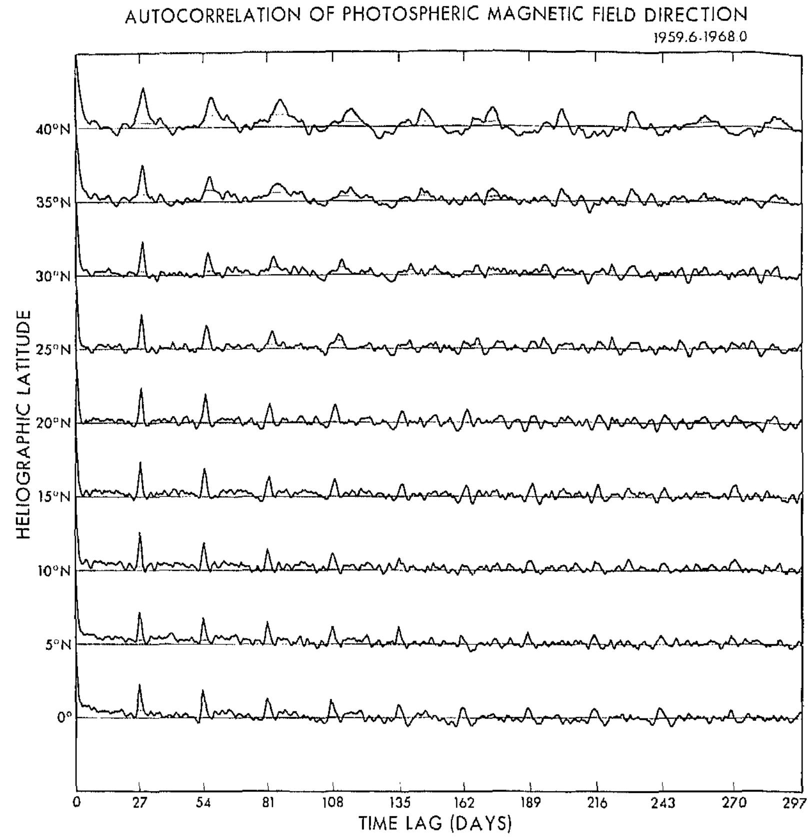


Fig. 3. Autocorrelation of the photospheric magnetic field direction versus lag for latitudes 40°–0°. The top curve represents the results for latitude 40°N. For this curve the horizontal line labelled 40°N represents an autocorrelation coefficient of zero, the horizontal line above it represents a coefficient of 1.0 and the horizontal line below it (which is labelled 35°N) represents a coefficient of $-1.0$. All other latitudes are displayed in the same format.

larger amplitudes than the adjacent peaks. Figure 4 shows the synodic rotation period associated with each recurrent peak in Figure 3. Figure 4 thus corresponds to the lower half of the schematic Figure 2. In Figure 4 the rotation period at each latitude corresponding to recurrence number 1 is approximately equal to the differential rotation results reported by Wilcox and Howard (1970). For the range of latitudes from 10°N–25°N the synodic rotation periods appear to be converging toward a constant value of $27.04 \pm 0.02$ days as the recurrence number increases (at 25°N the first recurrence peaks in Figure 3 appear to be a blend which becomes resolved at and after the sixth recurrence. Both parts of the blend are shaded in Figure 3 after they are resolved.)

Are the peaks selected for the larger recurrences physically significant? Consider the peaks in Figure 3 corresponding to the tenth recurrence (lag $\simeq 270$ days). If a peak adjacent to a shaded peak had been selected the lag would differ by about five days.

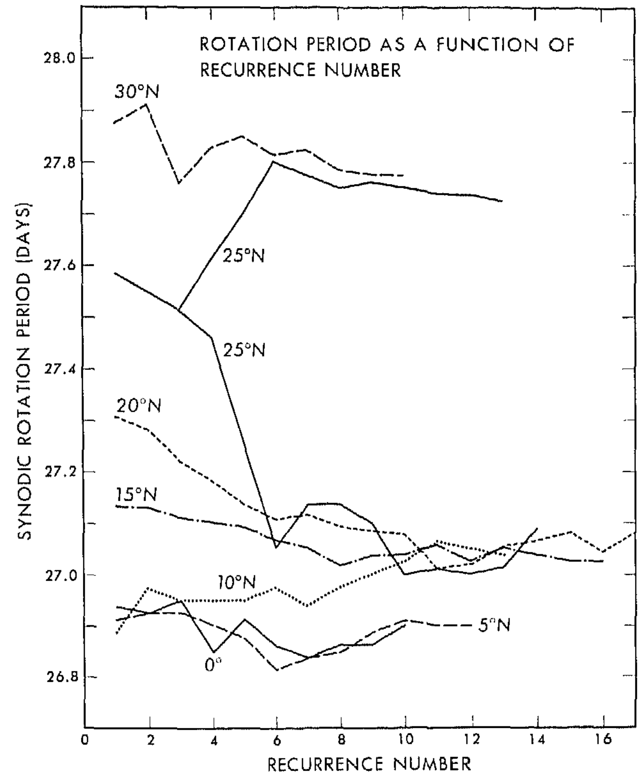


Fig. 4. Rotation period of the photospheric magnetic field as a function of recurrence number (see text) for latitudes 30°N–0°.

The associated rotation period would be

$$\tau'_{10} \simeq \frac{270 \pm 5}{10} \text{ days} = 27.0 \pm 0.5 \text{ days}.$$

Reference to recurrence numbers ten and larger in Figure 4 shows that this change of ~0.5 days is very large compared with the fluctuations (~0.05 days) of the periods corresponding to the chosen (shaded) peaks, and thus the selected peaks are significant.

Figure 5 shows the autocorrelation results over a range of latitudes from 40°S–0°. Figure 6 shows the resulting synodic rotation period as a function of recurrence number. In the southern hemisphere it is not possible to discern recurrence peaks beyond a few recurrences. This disappearance of the later recurrence peaks into the noise may be related to the generally lower magnitude of southern hemisphere fields observed during the interval analysed in the present investigation. The low signal-to-noise ratio in the south does not allow a possible rigidly rotating system with a period near 27 days to be seen. The autocorrelation peaks for latitudes 30°S–40°S in Figure 5 are approximately 180° wide, suggesting that a magnetic field pattern of similar width existed at these latitudes during most of the time interval investigated.

The rotation period corresponding to the first recurrence peak at each latitude in Figures 3 and 5 is plotted in Figure 7. From Figures 4 and 7 we see that at latitudes from 10°N–25°N the following situation obtains in the large-scale photospheric magnetic field: when each solar rotation is compared with the following rotation (i.e. recurrence number = 1) an autocorrelation analysis yields differential rotation, while when each solar rotation is compared with those rotations following it ten or

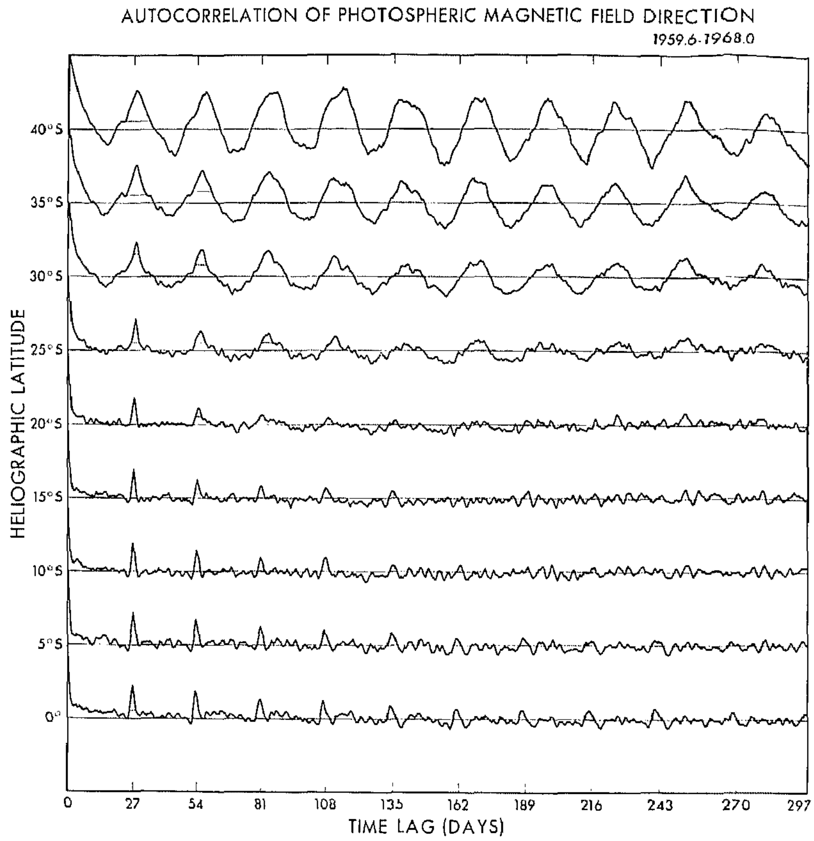


Fig. 5. Same as Figure 3, but for latitudes 40°S–0°.

more rotations later (i.e. recurrence number ⩾ 10) the same autocorrelation analysis yields rigid rotation with an average period of 27.04 ± 0.02 days. The precise relation of the rigidly rotating component discussed here to the solar sector structure discussed previously requires further investigation. Comparison of photospheric field observations with interplanetary field observations under favorable signal-to-noise conditions revealed a rigidly rotating solar sector structure over a range of heliographic latitudes from 40°N–40°S. These investigations covered portions of two years: 1964 (Wilcox and Howard, 1968) and 1965 (Schatten *et al.*, 1969). A comparison of the mean photospheric field and the interplanetary field (Wilcox *et al.*, 1969) during three solar rotations in 1968 was consistent with a rigidly rotating solar sector structure over a considerable range of heliographic latitude, but did not yield a measurement of its extent in latitude.

By comparison the present investigation with less favorable signal-to-noise conditions has yielded a rigidly rotating component in the photospheric field in the latitude range from 10°N–25°N during at least some part of the years 1959–1966. The present

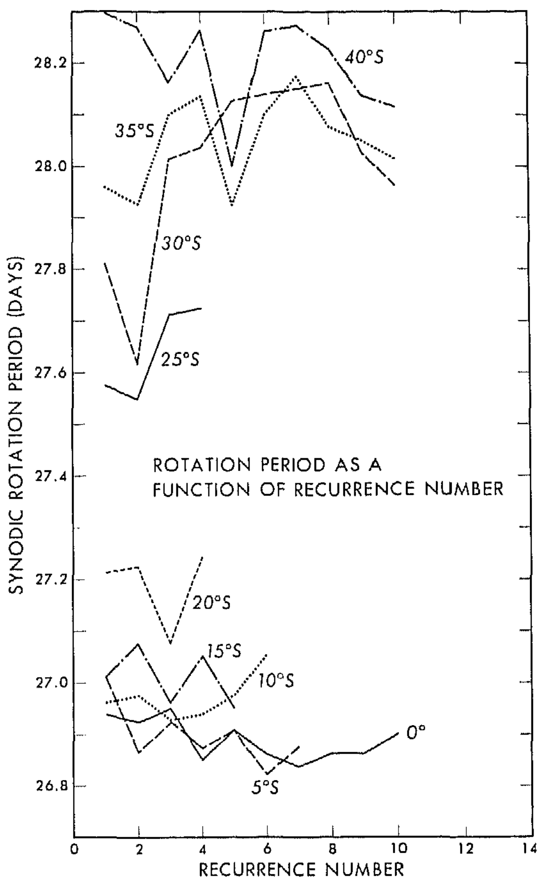


Fig. 6. Same as Figure 4, but for latitudes 40°S–0°.

analysis could not be extended to the appropriate recurrence numbers in the southern hemisphere, with the low signal-to-noise ratio in this region being ascribed to the generally weaker fields in the south.

This tendency for a dual interpretation of the low-latitude magnetic field behavior was pointed out by Bumba and Howard (1969) (see also Howard, 1967) who noted that although individual magnetic features, when they could be followed, rotated as nearly as could be determined with the angular velocity of the surface layers for that

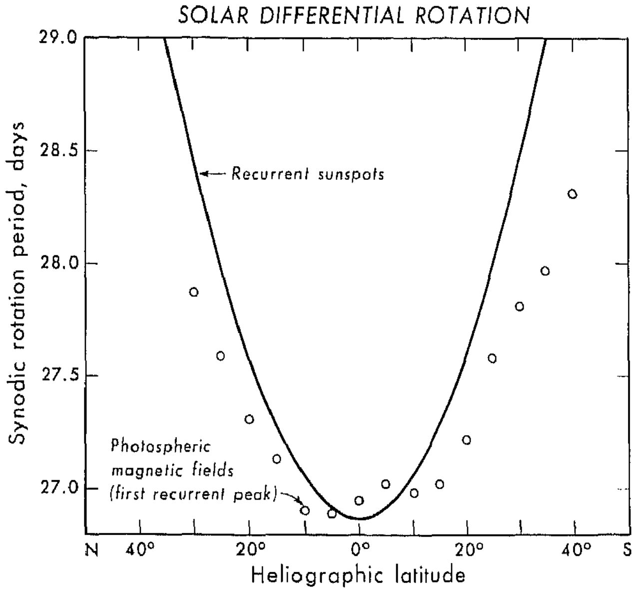


Fig. 7. Solar differential rotation. The solid curve represents the results of Newton and Nunn (1951) for long-lived sunspots. The circles are at the period associated with the first recurrence peak at each latitude in the autocorrelations of photospheric magnetic field direction in Figures 3 and 5.

latitude, the magnetic *patterns* which persisted for many months showed a rigid rotation period of 27.0 days over an interval of 20°N–20°S latitude.

The present investigation has revealed a dualism in the large-scale photospheric magnetic field, with a single latitude displaying *both* differential and rigid rotation properties.

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