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VARIATIONS IN THE SOLAR ROTATION RATE DERIVED FROM Ca^+ K PLAGE AREAS

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Abstract. Daily calcium plage areas for the period 1951–1981 (which include the solar cycle 19 and 20) have been used to derive the rotation period of the Sun at latitude belts 10–15° N, 15–20° N, 10–15° S, and 15–20° S and also for the entire visible solar disk. The mean rotation periods derived from 10–20° S and N, total active area and sunspot numbers were 27.5, 27.9, and 27.8 days (synodic), respectively. A power spectral analysis of the derived rotation rate as a function of time indicates that the rotation rate in each latitude belt varies over time scales ranging from the solar activity cycle, down to about 2 years. Variations in adjacent latitude belts are in phase, whereas those in different hemispheres are not correlated. The rotation rates derived from sunspot numbers also behave similarly though the dependence over the solar cycle are not very apparent. The total plage areas, integrated over the entire visible hemisphere of the Sun shows a dominant periodicity of 7 years in rotation rate, while the other time scales are also discernible.

1. Introduction

The solar rotation rate and its possible variation over time scales of less than one year as well as long-term trends have been studied among others by Howard and Harvey (1970), Howard (1976), Belvedere *et al.* (1977), and Livingston and Duvall (1979) from spectroscopic data. While Neidig (1980) has studied solar rotation using sunspots, Howard and Harvey (1970) have indicated that the rates determined from measured motions of sunspots or other features on the solar surface may be considered uncertain because it is impossible to be sure that the same point in the feature is measured from one time to the next. Though pattern-recognition process can be of some help in the identification of spots (Howard *et al.*, 1984), the center determined by fitting simple geometrical shapes to the spots still remains uncertain. Power spectral analyses (cf. Knight *et al.*, 1979; Bogart, 1982; Stimets and Londono, 1982; Keil and Worden, 1984) circumvent this problem. However, the results obtained from sunspot numbers may be affected by the differences between the rotation of different spot groups. Velocity measures from Doppler shifts of Fraunhofer lines have other limitations of accuracy of measurement of line shifts and the noise introduced by the local velocity fields on the solar surface. Hence, the differential rotation of the Sun is generally evaluated by taking an average of a large number of observations.

Belvedere *et al.* (1977) have shown that large evolved chromospheric faculae rotate more rigidly than the smaller ones. Also, large faculae have a life-time longer than the rotation period of the Sun. Hence, it is possible to obtain the solar rotation period using Ca^+ K plages. Bappu and Sivaraman (1971) have already shown that the time variation of total plage area on the visible hemisphere of the Sun indeed has the definite signature of rotation.

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On the other hand, it is difficult to derive the rotation rate from individual plages because one cannot identify a particular region of the plage on the Sun from one time to the next due to changes in the shape and size of the plage – a situation very similar to the one with sunspots, but even more severe. Therefore, we have adopted a simple technique of power spectral analysis of total plage area for finding the chromospheric rotation rate. The prime motivation was to develop a method for detecting the differential rotation in stars. Like sunspots, plages develop at high latitudes at the beginning of the solar cycle, and move progressively toward lower latitudes as the cycle ages. Thus by determining the rotation period as a function of time from the total palge area measurements, one can, in principle, find the rotation periods of different latitude belts. The rotation periods are hence expected to show systematic variations in phase with the solar cycle. If they indeed do, one may then hope to extend this method to stars by simply replacing the plage areas with the Ca^+ K line intensity, though the extended background chromospheric emission would add to the difficulties in the stellar case.

We performed first a power spectral analysis of plage areas for the period 1951–1981, integrated over the entire visible solar disk. The derived solar rotation rate showed variations on time scales even smaller than the 11-yr solar cycle. In order to investigate this phenomenon, we repeated our analysis for individual latitude belts and also for the total sunspot numbers. The results of these analyses are discussed in the present paper.

2. The Data and Analysis

We have used sun chart data for the period 1951–1981 obtained from Kodaikanal K_{232} spectroheliograms. The data consist of measured active area (in millionths of the visible hemisphere) in 5° latitude intervals and over 180° visible longitude. These are available at the observatory in tabular form, and are based on the spectroheliograms routinely obtained at an image scale of 33 arc sec mm^{-1} and with a spectral band pass of 1.1 Å. We have confined ourselves to four latitude belts, 10–15° N, 15–20° N, 10–15° S, and 15–20° S, because these belts have active regions most of the time, whereas other belts have active regions only for about five years in a solar cycle. We have also utilized total active areas and sunspot relative numbers in the analysis.

If a day was cloudy, we took the mean of adjacent days for which data were available so as to form continuous data. Raw power spectra were obtained through fast Fourier transform (FFT) for data strings of 512 days. The mean was subtracted out and the ends apodized before performing the FFT. A lag of 64 days was provided in forming successive data strings. Thus the data for 384 days are common to successive intervals. This was done to ensure continuous information about the chromospheric rotation period. The total data length of 11 328 days thus gave us 170 epochs separated by 64-day intervals. The length of 512 days was adopted after initial analysis with 1024 days showed double peaks in the power spectra at $\sim$27 days suggesting that the rotation period varies over time scales shorter than the total data length.

The solar rotation gives rise to a conspicuous peak in the range 25–33 days (synodic) in the power spectra (see e.g. Figure 1). Generally this is the most dominant peak,

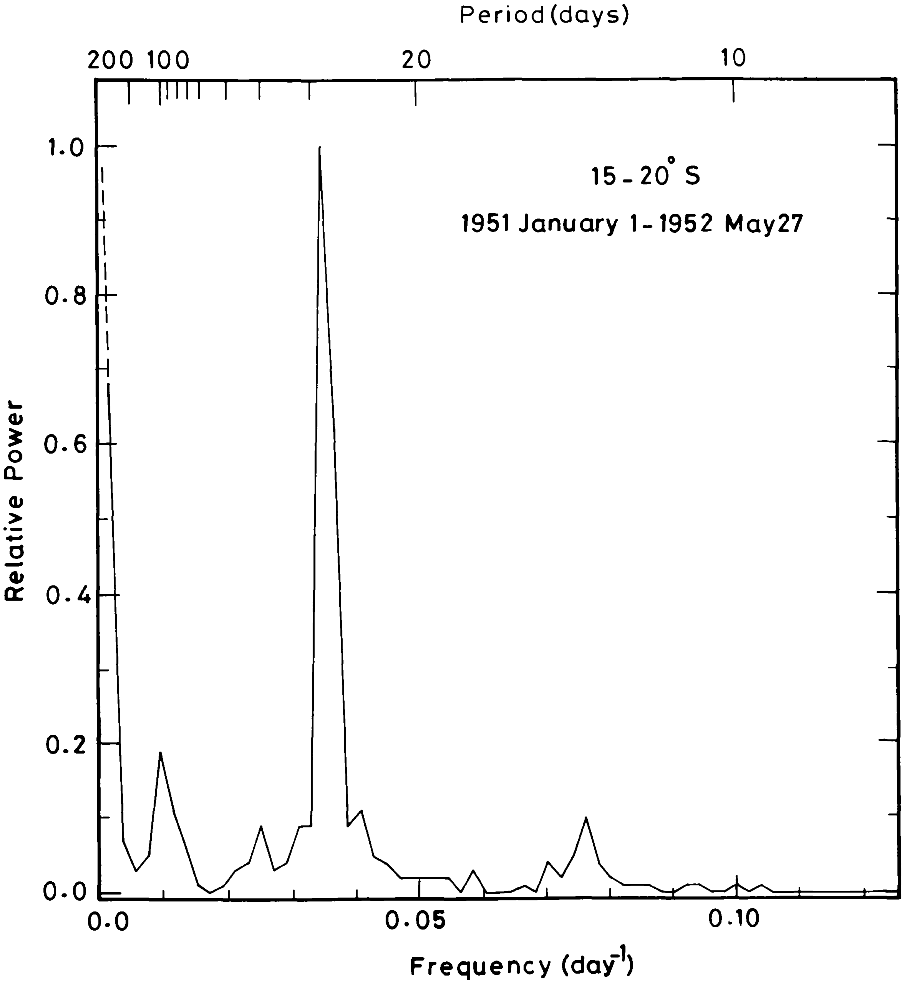

Fig. 1. A sample of raw power spectra of 512-day data showing clearly the rotation period.

though when one solar cycle ends and another begins there appears a peak at ~ 250 days (about half the data string) due to a change in the total plage area. The effect of the value of lag on the derived rotation period was tested by performing the analysis for a section of the data (512 days) using different lags of 16, 19, and 64 days. It was evident that the adopted value of lag has no effect on the results obtained. We have analysed the same section of data also by averaging over successive 2 and 4 days. Again, the results remain the same. These experiments affirmed our faith in the reality of observed variations in the rotation period. We have also corrected a part of the data for the effect of foreshortening and found that the derived periods agree well with those derived from the uncorrected data. Hence, the data used in the final analysis were not corrected for foreshortening.

The power spectra also show a few weaker peaks ($< 30\%$ of the peak due to rotation). Among these is a period of ~ 13 days (cf. Figure 1). A similar period (~ 12.07 d) was also seen by Knight *et al.* (1979) in sunspot data, which caused considerable excitement due to its close agreement with the 12.22 d photospheric perturbation predicted by Dicke (1976) based on the assumption of faster core rotation. We will not comment on this peak in the present paper, but note that it appears to be present, and is fairly stable.

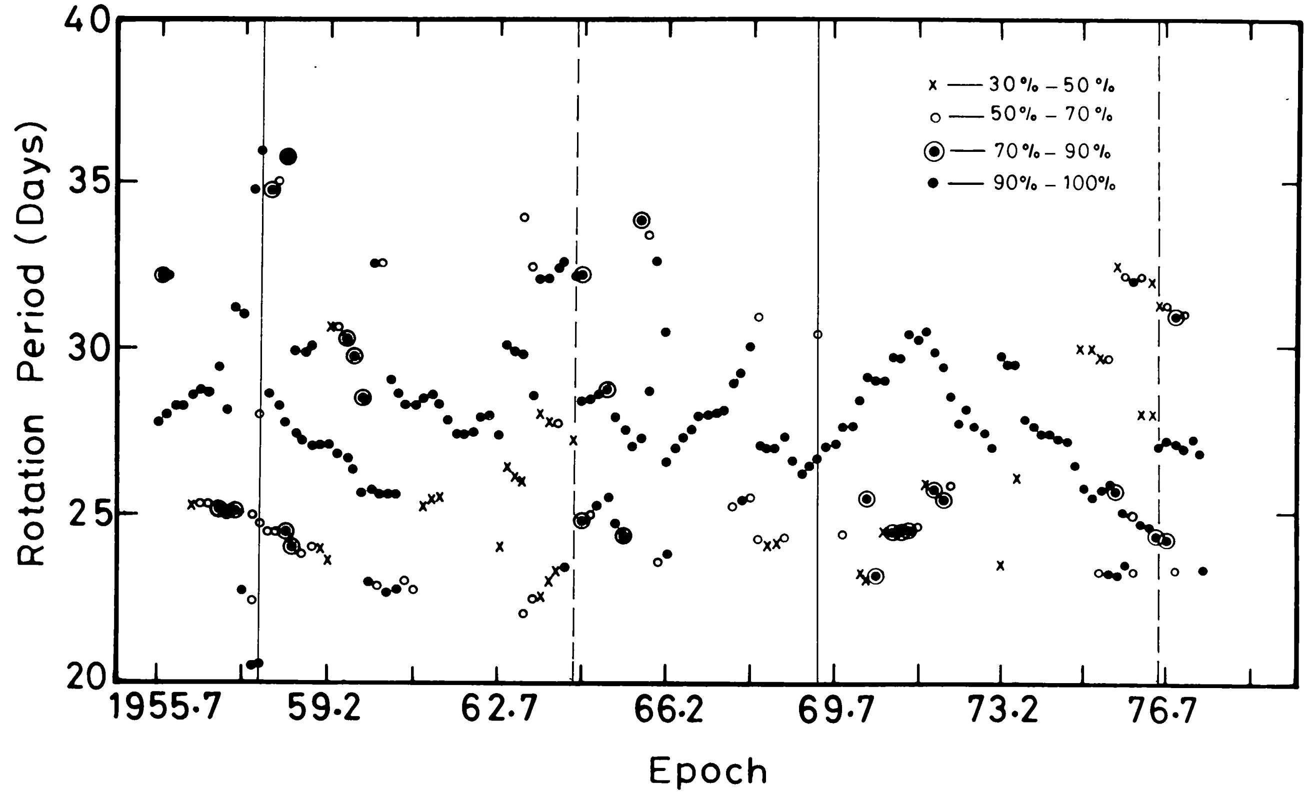

Fig. 2. All the observed periodicities (synodic) for the plage areas integrated over the entire visible disk of the Sun. Periods are classified according to their strength relative to the strongest peak in the power spectrum. The solid vertical lines correspond to the solar maximum and the dashed ones, solar minimum.

3. Results

Initially we used the data on plage areas integrated over the entire visible disk of the Sun and counted all peaks between 20 and 40 days. The power spectrum in this region was normalized with respect to the strongest peak, and all the peaks upto 30% of the maximum power were considered. The peaks were determined by Fourier interpolation at an interval one-fifth of the FFT resolution. The derived periods were divided into four groups depending on their relative power: (i) 90–100%, (ii) 70–90%, (iii) 50–70%, and (iv) 30–50%. All these periods are plotted in Figure 2 as a function of time for the years 1955–1976. The epoch in this figure and elsewhere are central to the corresponding data string. It appears from the figure that there often exist three distinct rotation periods at any given epoch, each of which varies continuously. The three periods are better seen between 1955–1962 when there appears to be a general decrease in each period. One may conjecture that these different periods correspond to different latitude belts and arise due to solar differential rotation. In such an event, one should observe a general decrease in the periods as the solar cycle progresses since plages occur at increasingly lower latitudes. This appears to be so between 1957 and 1961, soon after the maximum of cycle 19. On the other hand, the dominant rotation period appears to have minima both around 1969 and 1976, the maximum and minimum of cycle 20, with a peak in rotation period in between. Such a behaviour is possible if the rotation rate varied with a period of 7 years so that three such cycles are completed in two cycles of solar activity.

In order to understand the phenomenon better, we analysed the data grouped into different latitude belts, considering only the 10°–15° and 15°–20° belts in both the north and south hemispheres where plages are seen all through the solar cycle. The

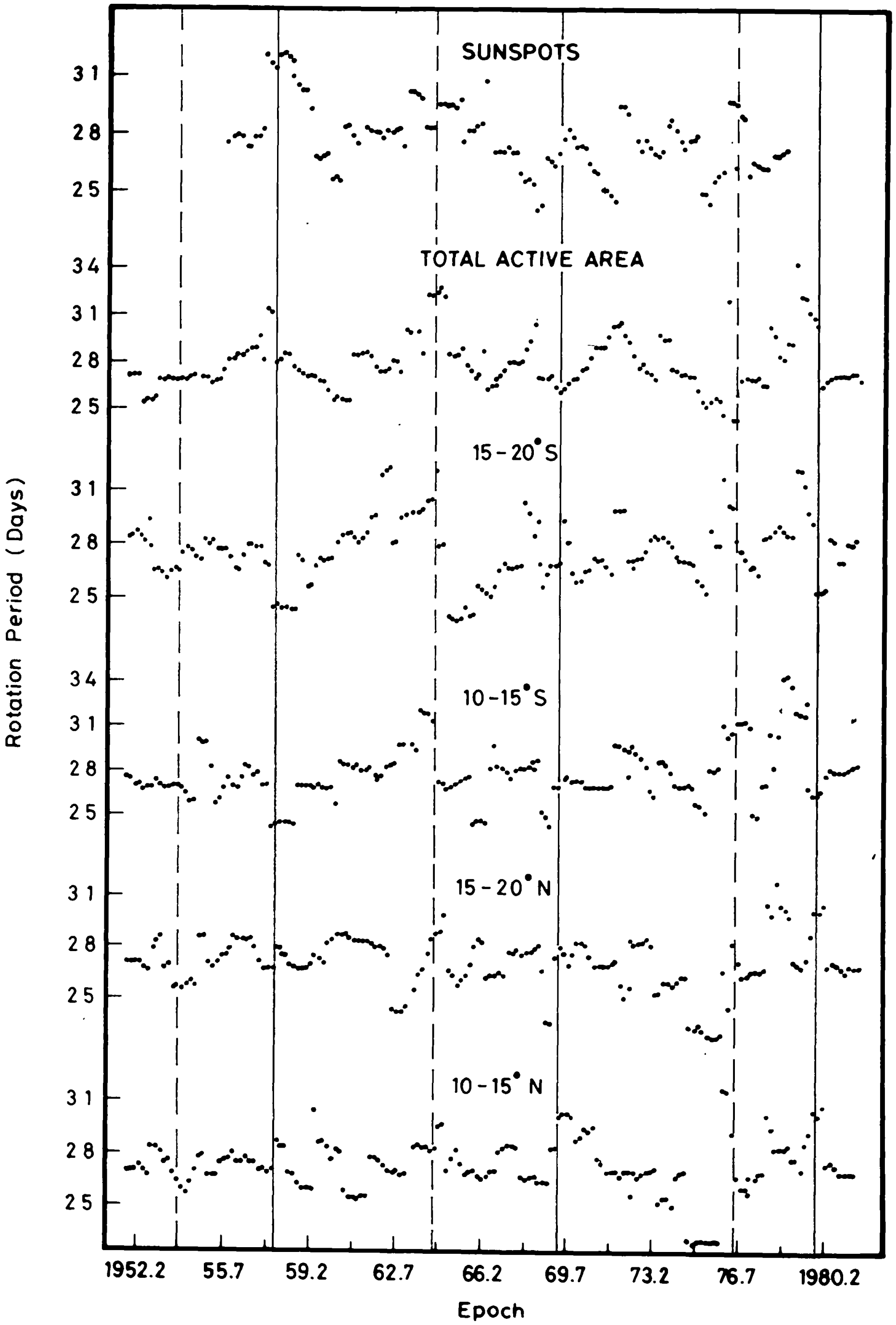

Fig. 3. Variation of the (synodic) rotation period with time, derived from the sunspots, total active area, and active area at different latitude belts. The epochs of solar maximum (solid lines) and minimum (dashed lines) are also marked.

derived rotation periods are plotted as a function of time in Figure 3 for various latitudes. Only the strongest peak at each epoch was considered. We add for comparison the periods obtained from total active area over the entire visible disk and also from sunspot numbers. The mean synodic rotation periods in days are 27.2 ± 1.6 (15°–20° N), 27.4 ± 1.5 (10°–15° N), 27.9 ± 1.9 (10°–15° S), 27.5 ± 1.8 (15°–20° S), 27.9 ± 1.7 (total active area), and 27.8 ± 1.7 (sunspot numbers). Converting the mean synodic period between 1966–1978 to sidereal rate we obtain a mean chromospheric rotation rate of 14.11° day^{-1} from 10°–20° N and S belts, and 13.94° days^{-1} from integrated areas. These values may be compared with the mean chromospheric rotation rate of 14.39° day^{-1} derived by Livingston and Duvall (1979) for the same period but between latitudes ± 20°, i.e., including the equatorial belt.

From Figure 3, it is obvious that the rotation period changes with time quasi-periodically. To estimate the periodicities of variation in rotation period, we carried out a further power spectral analysis of these periods for each latitude belt as well as for the total active area and for sunspot numbers. In addition to estimating the periodicity from power spectra (Figures 4 and 5), we also used the maximum entropy method utilizing the discrete Fourier transform. The prominent peaks are listed in Table I. We notice a multiplicity of periodicities in the range 1–22 years. The time scales around 2, 7, and 11 years appear most frequently.

With a view to determining if these changes are global or localized, we have computed correlation coefficients between the rotation data for various belts. These are listed in Table II. The correlation coefficients for 10–15° N and 15–20° N, and 10–15° S with 15–20° S belts are 0.576 and 0.605, respectively. For these values (n = 170), the confidence level is better than 99%. The correlation coefficient between periods derived

TABLE I

Derived periodicities (in years) in solar rotation

10–15° N	11.82	7.29	3.27	1.78
	11.22	6.96	3.35	2.31, 2.01, 1.79
15–20° N	–	8.50	–	1.98
	10.44	5.68	–	1.99, 1.78
10–15° S	9.43	–	–	2.19
	–	7.81	3.80, 3.05	2.41, 2.15
15–20° S	10.35	6.10	–	2.50
	–	8.12	3.94	2.40
Average of 10–20° N and S	10.65 ±0.91	7.22 ±0.91	3.48 ±0.37	2.11 ±0.26
Total active area	–	7.02	–	–
	–	7.48	–	–
Sunspots	–	7.29	3.72	2.13, 1.43
	–	6.80	3.90	2.24, 1.40

Note: The first line in each category is derived from MEM method whereas the second line from raw power spectra. Only periods shorter than ~11 yr, and stronger than 30% of the strongest peak are listed.

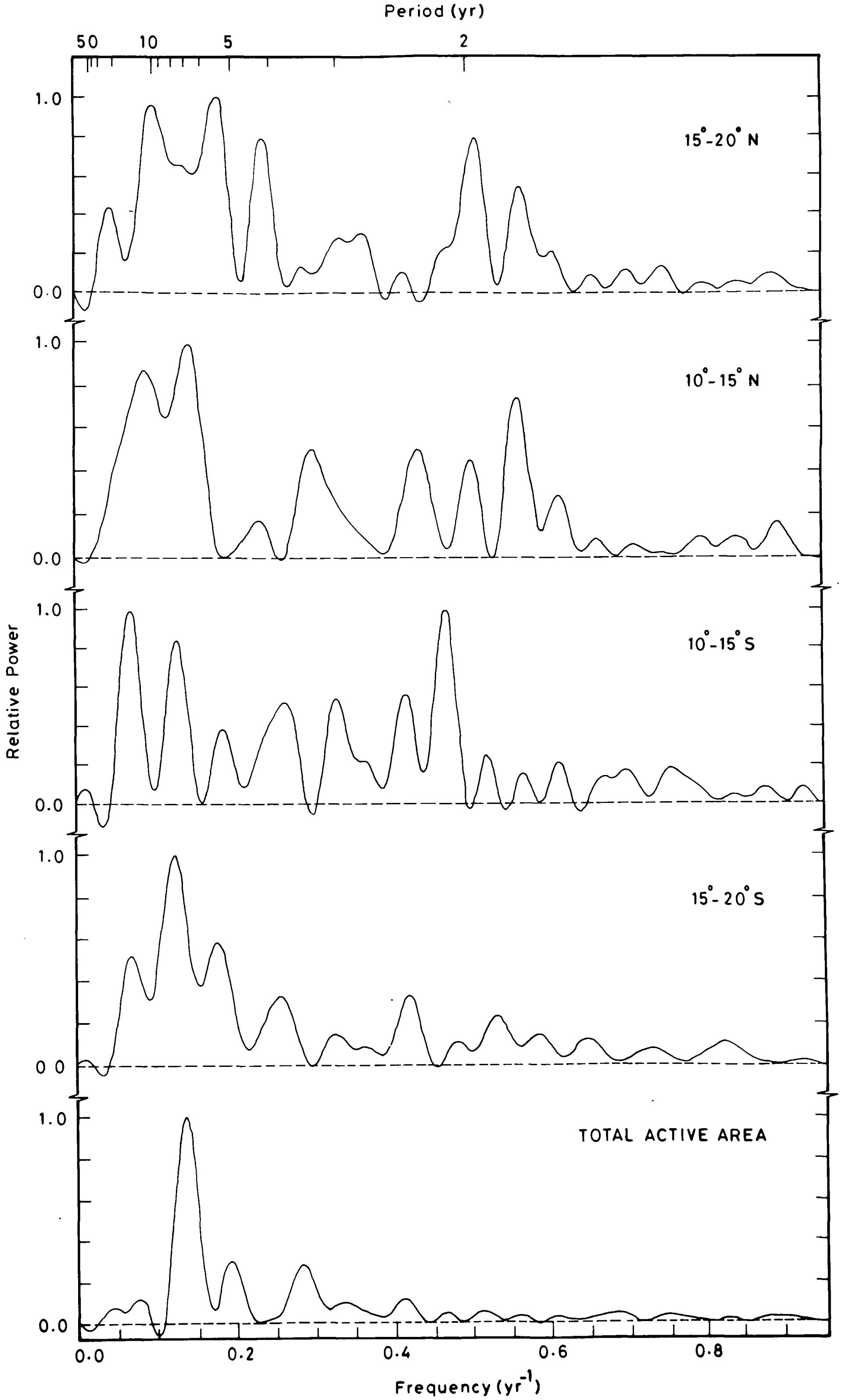

Fig. 4. The power spectra of rotation period as a function of epoch as derived from plage areas in different latitude belts as well as from the entire disk. This figure and also the next have been enlarged from the original power spectrum by a factor of 5, using Fourier interpolation technique. In both these figures, a small amount of overshooting to negative powers is caused by this procedure.

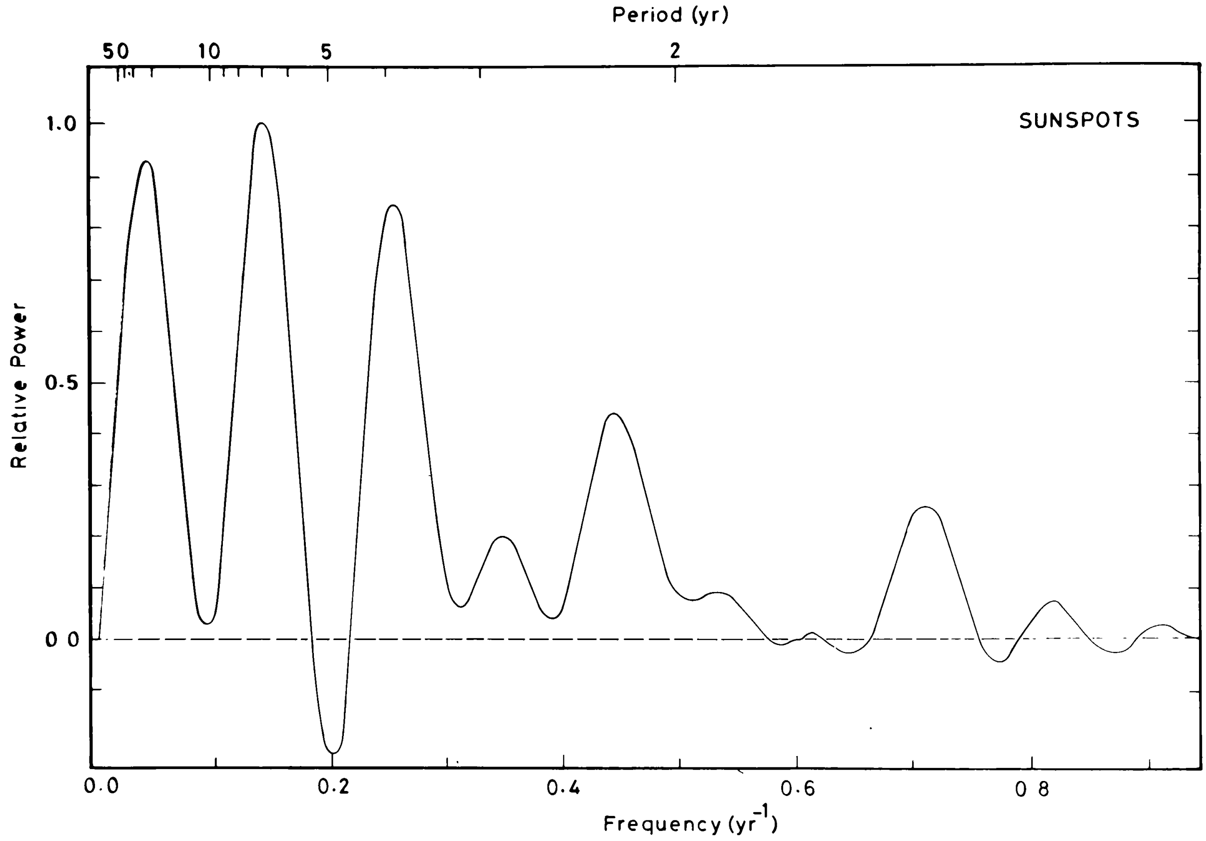

Fig. 5. The power spectrum of rotation period derived from sunspot numbers.

TABLE II

Correlation coefficients between different data sets

	10–15° N	10–15° S	15–20° S
15–20° N	0.576	0.157	0.104
10–15° N	–	0.114	0.106
10–15° S	0.114	–	0.605

Sunspot numbers and total active area have a correlation coefficient of 0.259 for 129 data points. All the data sets in the table have 170 points each.

from total active area and sunspot numbers is 0.259 with a confidence level of about 98% ($n = 129$). We have also computed the cross-correlation function, which, for adjacent latitude belts, decreases with increasing phase lag, showing that there is a good degree of coherence. On the other hand, the correlation coefficient between northern and southern latitude belts is much smaller (~ 0.1). This indicates that the changes in rotation occur on a latitude belt of width $\gtrsim 10°$, but the variations are not in phase on a global scale. There is no north–south symmetry.

4. Discussion

Three major conclusions appear from the above analysis:

(i) The active area measured using Ca^+ K plages provides an effective tool for deriving solar rotation rate.

(ii) The chromospheric rotation rate varies not only with the solar activity cycle, but also on shorter time scales, the stablest of which appear to be around 2 and 7 years.

(iii) The rotation rate varies in phase over a fairly wide belt in latitude ($\gtrsim 10°$ in width), but not on a global scale.

It might appear that our results are affected by the changes in shape and sizes of plages that may induce a migration of the mean longitude. However, in order to produce the observed variations, we need to contrive a highly systematic evolution of the shapes of plages as a function of the epoch of their formation. On the other hand, variations in rotational velocity can easily be induced by torsional oscillations on the Sun (LaBonte and Howard, 1982).

Livingston and Duvall (1979) have studied the variation of rotational velocity inferred from spectroscopic data over the latitude range $\pm 20°$. However, they find a linear increase in solar rotation rate by $\sim 3.7\%$ during the period 1966–78. The short-period variations could not have been detected by them due to an insufficient number of observations. A linear fit to our data for the same 12-year period shows an increase of 3.7%, 6.6%, and 1.0% for the integrated, 10–15° N and 15–20° N data, respectively. The data for 10–15° S, 15–20° S and sunspots, however, show a decrease in rotation rate by 6.2, 3.6, and 4.6%, respectively. Furthermore, these values are not significant compared to the amplitude of quasi-periodic variations ($\sim 12\%$).

Howard and LaBonte (1980) have detected torsional oscillations on the Sun with a period of 11 years. The wave-pattern of oscillations, which is symmetric about the equator, consists of four alternating zones of fast and slow rotation over each hemisphere. The whole pattern propagates from the poles to equator with a time scale of about 22 years. The quasi-periodicities detected by us, however, do not appear to have a global pattern. An extension of the analysis to a larger number of latitude belts on the Sun is planned in an attempt to understand this aspect better.

It will be of interest to compare the quasi-periodicities detected by us with the periodicities in other kinds of solar phenomena. Their existence in the sunspot numbers was pointed out over two decades ago by Shapiro and Ward (1962). Sakurai (1979) found that the data on solar neutrino flux for the period 1970–75 showed a periodicity of ~ 2.1 years and also correlated well with sunspot numbers. Based on more extensive data (1970–81), Haubold and Gerth (1983) detected a range of periodicities (0.53, 0.73, 1.27, 1.63, 2.13, 2.98, 4.90, and 8.33 yr), the 2.1 yr periodicity being among the prominent ones. Similarly, $\lambda 10$ cm flux data for the period 1947–78 analysed by Hughes and Kesteven (1981) showed periodicities of 2.1 and 3.0 yr. It is surprising to find the 2-year time scale so common between totally different types of observations. A physical explanation connecting all these diverse phenomena will certainly be challenging.

The seven-year periodicity, which is the most dominant one in the total active area, is also intriguing. It has the same time scale as the duration from solar maximum to