# DEPTH DEPENDENCE OF THE PERIODICITIES IN SOLAR DIFFERENTIAL ROTATION

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## ABSTRACT

We study the temporal variations of the differential rotation coefficient $B$ by determining it separately from Greenwich data (1879-1939) samples defined as follows: (i) YLSG: *young long-lived sunspot groups* (YLSG1: $t = 2$, $\tau$ = 7-12, or YLSG2: $t < 4$, $\tau$ = 10-12), where $\tau$ and $t$ represent respectively life span and age of a sunspot group in days, (ii) SLSG: *short-lived sunspot groups* ($\tau$ = 2-4) and (iii) OLSG: *old long-lived sunspot groups* ($t > 4$, $\tau$ = 10-12). The Fourier power spectrum of $B$ determined from the YLSG shows existence of a prominent periodicity of ~ 21 yr. Spectra determined from the OLSG and SLSG show existence of a prominent periodicity of ~ 11 yr. Comparing the mean rotation frequencies of the YLSG, OLSG and SLSG with the radial dependence of solar plasma rotation frequency determined from helioseismology, it is suggested that the periodicities ~ 21 yr and ~ 11 yr in $B$ are dominant in the rotational perturbations in the Sun's deeper layers (near base of the convective envelope, $r \sim 0.73 R_\odot$) and in the shallower layers ($\sim r > 0.95 R_\odot$) respectively. However, these results have to be confirmed from the analysis of sunspot data for later periods and from the helioseismical determination of the temporal variations of differential rotation of the Sun's internal layers.

Key words: solar internal rotation; sunspot rotation.

## 1. INTRODUCTION

The study of temporal variations in Sun's differential rotation is vital for understanding the physical process responsible for the solar activity and the solar cycle. Earlier, we analyzed the Greenwich data on sunspot groups during 1879-1976 and detected various periodicities in the range 2-45 yr, including one at '~ 20 yr' in the ratio $B/A$ (and in $B$) of the coefficients of differential rotation (Javaraiah & Gokhale 1995, hereafter Paper I). The '11 yr' periodicity was found to be weak or absent. We also found existence of '45 yr', '21.3 yr', '13.3 yr' and '10.5 yr' periodicities in the north-south asymmetry of $B$ (Javaraiah & Gokhale 1997a, hereafter Paper II). Recently, we noticed existence of differences in the periodicities (in the range 2-11 yr) in the differential rotation determined from the sunspot data and the Mt. Wilson velocity data. It was speculated that this difference could be because the rotation rates determined from the two data sets may represent the rotation rates of solar plasma at different radial distances (Javaraiah & Komm 1998, hereafter Paper III).

The solar rotation rate determined from sunspots or sunspot groups depends on which class of spots or spot groups is used, e.g., on the size, life span, and age of the sunspot groups (e.g., Schröter 1985). Recently, we analyzed sunspot group data during 1874-1939 and showed, (Javaraiah & Gokhale 1997b), that : (i) the magnetic structures of the spot groups which live successively longer by 1 day may be initially anchored in successively deeper layers by ~ 21000 km, (ii) the structures which yield spot groups of life span 10-12 days are initially anchored near the base of the convective envelope, and (iii) for a spot group which lives 10-12 days in latitudes $10^o - 20^o$ the 'anchoring layer' of its magnetic structure also rises at a rate ~ 21000 km per day, as the spot group ages. These results were derived by maximizing the correlation between the radial variation of the plasma rotation frequency determined from helioseismology and the variations of rotation frequency of sunspot groups with life span ($\tau$, in days) and age ($t$, in days).

In view of these results we have studied in the present paper, the periodicities in $B$ obtained separately from well defined data samples of young, old and short-lived sunspot groups.

The main conclusion is that the '21 yr' and the '11 yr' periodicities are dominant in the differential rotation of the plasma near the base and the top of the Sun's convective envelope respectively.

## 2. DATA ANALYSIS

The data and the method of reduction is same as in Javaraiah & Gokhale (1997b). The magnetic tape of the GPR data on the sunspot groups during years 1874-1976 was kindly provided by Dr. H. Balthasar. This includes the observation time (the date and the fraction of the day), heliographic latitude, and longitude for each spot group on each day of its observation, besides other parameters.

In the present study also we have to ensure that we know unambiguously the first and the last days of the life spans of the sunspot groups. For period 1940-1976, the data corresponding to the days when the

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*Proceedings of the SOHO 6/GONG 98 Workshop, 'Structure and Dynamics of the Interior of the Sun and Sun-like Stars', Boston, USA, 1-4 June 1998 (ESA SP-418, October 1998)*

central meridian longitude (CML) of a spot group is beyond −58° or +58°, are not available. Hence here we analyze the data during 1879-1939 only. Even from the years 1874-1939 we have eliminated the entire data on those spot groups which have $|CML| > 75°$ on any day of their life span. (This leads to elimination of the second and the subsequent disc passages of the recurrent spot groups.) Thus, all spot groups with identifiable first and last days, have life spans $\leq$ 12 days.

In view of the relationships, found earlier (Javaraiah & Gokhale 1997b), between the rotation frequencies of the spot groups and the life span and age of the spot groups, we consider separately the following data samples defined as follows: (i) YLSG: ***young long-lived sunspot groups*** (YLSG1: $t = 2$, $\tau =$ 7-12, or YLSG2: $t < 4$, $\tau =$ 10-12), where $\tau$ and $t$ represent respectively life span and age of a sunspot group in days, (ii) SLSG: ***short-lived sunspot groups*** ($\tau =$ 2-4) and (iii) OLSG: ***old long-lived sunspot groups*** ($t > 4$, $\tau =$ 10-12).

For these well separated data we fitted the standard formula of differential rotation:

$$\omega(\lambda) = A + Bsin^2\lambda, \tag{1}$$

where $\omega(\lambda)$ is the solar rotation rate at latitude $\lambda$, $A$ and $B$ represent the equatorial rotation rate and the latitudinal gradient of the rotation rate respectively.

For each of the above data sets, we determined variations of $B$ during 5-yr moving time intervals successively displaced by 1 yr (5-yr MTI) (the data sizes in the intervals < 5-yr are inadequate). We excluded the data corresponding to the 'abnormal' motions, e.g., displacements exceeding $3^o$ $day^{-1}$ in longitude or $2^o$ $day^{-1}$ in latitude. This reduces the data samples by about 3% but guards against errors in recording and in identifying of small spot groups from one day to the next (Ward 1966). This precaution substantially reduces the uncertainties in the values of $A$ and $B$ (cf. Paper I).

## 3. TEMPORAL VARIATIONS OF $B$

Figure 1 shows the variations of $B$ during 5-yr MTI of YLSG1, YLSG2, OLSG and SLSG. In this figure it can be seen that the uncertainty bars are sufficiently small for seeing the variations of $B$ (determined from YLSG1, YLSG2 and OLSG) on time scales 10-20 yr.

### 3.1. Periodicities in $B$

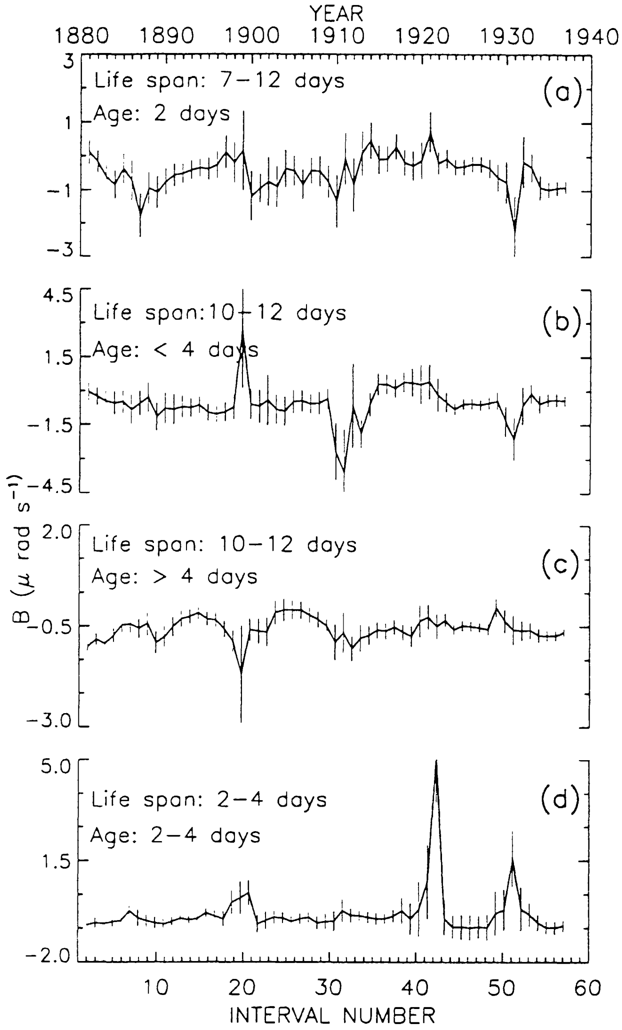

*Figure 1. Variation of the differential rotation coefficient B (Eq. 1) determined from the two subsets (a) YLSG1 and (b) YLSG2 of YLSG: young long-lived sunspot groups, (c) OLSG: old long-lived sunspot groups and (d) SLSG: short-lived sunspot groups. The successive 5-yr intervals 1879-1883, 1880-1884, ......., 1935-1939 are denoted by the interval numbers 1, 2, ....., 57 respectively, shown on the bottom scale. The middle years of these intervals are shown in the top scale.*

We have determined FFT spectra of the sequences of $B$ derived from YLSG1, YLSG2, OLSG and SLSG for 5-yr MTI. For this we followed the same procedure as described earlier (cf. Papers I, II and III). While computing the FFT of any sequence of values, a first-order polynomial fit obtained from the whole sequence is first subtracted from each value. Next the first and the last 10% of the data is apodised by using a cosine bell function and then the size of the sequence is extended to the next power of 2 by taking an adequate number of zero values. This detrends the sequence and removes the leakage between the repeated data segments (Brault & White 1971). Figure 2 shows the FFT spectra of $B$ determined from the YLSG, OLSG and SLSG for 5-yr MTI during 1879-1976. (For longer interval lengths the uncertainties in $B$ will be smaller. However, the peaks corresponding to the higher frequencies will be washed out, and the peaks at lower frequencies will be broader.) The FFT spectra $B$ determined from the YLSG show existence of a periodicity at ~ 21 yr. This periodicity is absent (or insignificant), and a ~ 11 yr periodicity is dominant in the spectra of $B$ determined from the OLSG and SLSG.

To check whether the positions and significance levels of the peaks in the FFT spectra of $B$ are reliable in spite of the uncertainties (standard deviations) in the

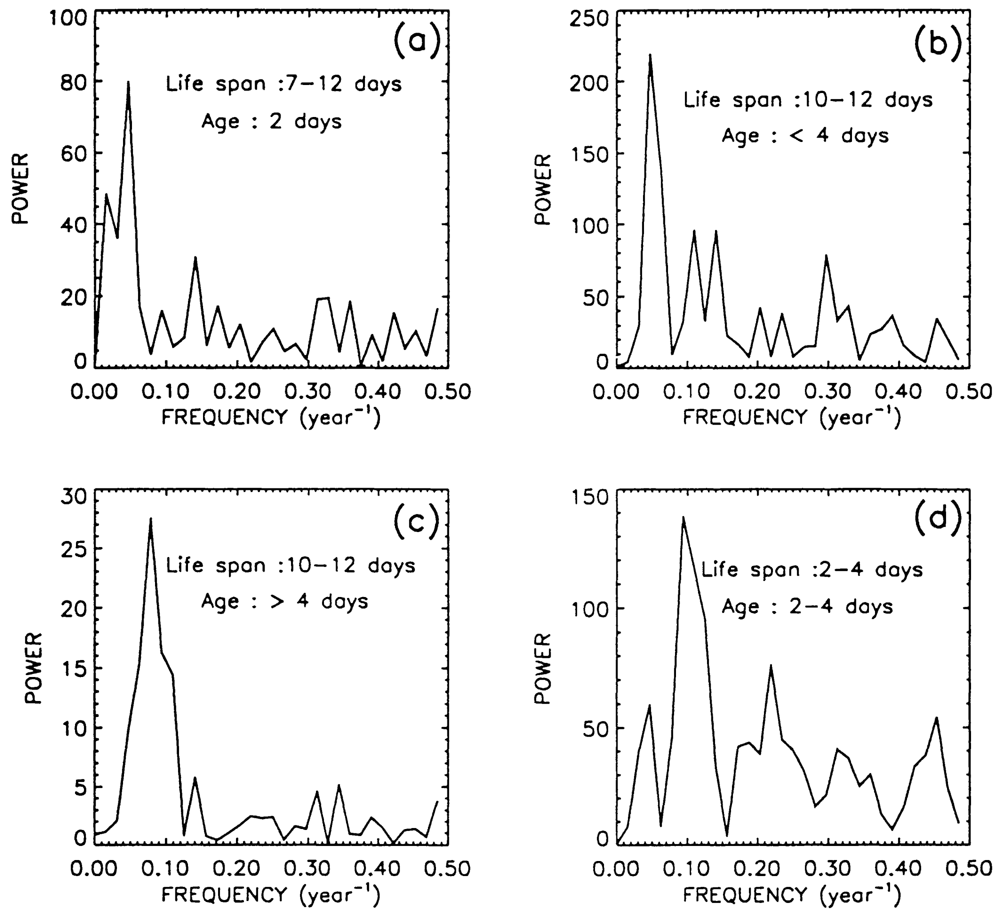

*Figure 2. FFT spectra of $B$ determined from the (a) YLSG1, (b) YLSG2, (c) OLSG and (d) SLSG.*

values of $B$, we used the following method which we have already used in Papers I and II. We generated 'simulated' time series $B'$ of $B$ by varying each value of $B$ in the time series by adding to it a random number whose magnitude is equal or less than the corresponding uncertainty. FFT analyses were then done for the simulated series of $B'$. In both spectra of $B$ and $B'$ determined from a given data set, the positions of the peaks were found to be the same. Thus, even if the 'correct' values of $B$ were any where within their respective standard deviations, the positions of the peaks in FFT spectra would be unaltered. Hence, the peaks in the FFT spectra of $B$ represent the true variations of $B$.

## 4. DEPTH DEPENDENCE OF ROTATION FREQUENCIES OF THE YLSG, OLSG AND SLSG

In figure 3, we compare the average rotation frequencies ($\omega$) of YLSG, OLSG and SLSG with the radial dependence ($\Omega(r)$) of plasma rotation frequency determined from helioseismology. From Figure 3, we infer that the average rotation frequency determined from the YLSG represents the average rotation frequency of magnetic structures of YLSG which are initially anchored (or born) in deeper layers (near the base of the convective envelope, $r/R_\odot \sim 0.73$), whereas the average rotation frequencies determined from the OLSG and SLSG represent the average rotation frequencies of their magnetic structures which are anchored at $r/R_\odot > 0.95$.

## 5. CONCLUSIONS AND DISCUSSION

From the results in Sections 3 and 4, we conclude the following:

(1). $\sim$ 21 yr periodicity is dominant in $B$ determined from the YLSG, whereas in $B$ determined from the OLSG and SLSG $\sim$ 11 yr periodicity is dominant.

(2). The average rotation frequency of YLSG represents the rotation of their magnetic structures which

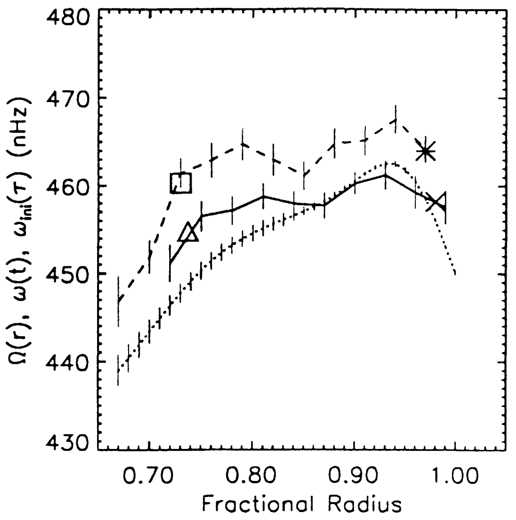

*Figure 3. The dotted curve represents radial variation of rotation frequency of solar plasma* $(\Omega(r))$ *at latitude* $15^o$ *as provided to us by Dr. H. M. Antia, who determined it from the Big Bear Solar Observatory (BBSO) helioseismic data (Woodard & Libberecht 1993) using the inversion method of Antia & Chitre (1996). Dashed curve represents variation of initial rotation frequency with life-span of the spot groups,* $\omega_{ini}(\tau)$*, in the entire sunspot latitude belt and the continuous curve represents the variation of rotation frequency with age,* $\omega(t)$*, of the spot groups in the latitude interval* $10^o - 20^o$*. These are given by maximized correlations with* $\Omega(r)$ *at latitude* $15^o$*, (the dotted curve). From left to right the values of t are 1.5, 2.5,...,10.5 days, and those of* $\tau$ *are 11.5, 10.5,...,1.5 days respectively (Javaraiah & Gokhale 1997b). The symbols SQUARE, TRIANGLE, CROSS and STAR represent the average rotation frequencies of the YLSG1, YLSG2, OLSG and SLSG respectively and they were determined from the data during entire period 1874-1939.*

are initially anchored near the base of the convective envelope, whereas the average rotation frequencies of OLSG and SLSG represent the rotation frequencies of their magnetic structures anchored in shallower layers near the surface.

(3). From conclusions (1) and (2) we conclude that (i) the ~ 21 yr periodicity in $B$ is dominant in the rotational perturbations in the deeper layers (near the base of the convective envelope, $r \sim 0.73 R_\odot$), (ii) the ~ 11 yr periodicity obtained from the OLSG and SLSG, and obtained earlier from Mt. Wilson/NSO Kitt Peak velocity and magnetogram data (LaBonte & Howard 1982; Snodgrass & Howard 1985, Komm et al. 1993), is dominant in the rotational perturbations in the shallower layers of the Sun ($\sim r > 0.95 R_\odot$).

The effects of differential buoyancy (D'Silva & Howard 1994) or difference in inclination between preceding and following wings of the rising fluxtube (Caligari et al. 1995) might cause sunspots to rotate slightly faster than local plasma rotation rate. However, in spite of the effects (if any) due to aforementioned factors, the mean variation of the 'initial' rotational frequency, $\omega_{ini}(\tau)$, of sunspot groups, with life spans of spot groups in the range 12 to 2 days, has its trend similar to the variation of plasma rotational frequency, $\Omega(r)$, across the convective envelope (see Figure 3). Hence, the conclusion (3) above, holds good in spite of the effects (if any) due to aforementioned factors. However, this has to be confirmed from the analysis of sunspot data for later periods and from helioseismical determination of temporal variations of the differential rotation of Sun's internal layers.

## ACKNOWLEDGMENTS

I am thankful to Prof. M. H. Gokhale for discussion and useful suggestions. I thank Dr. H. M. Antia for providing the values of $\Omega(r)$ and Dr. R. F. Howard for useful comments. I gratefully acknowledge SOHO 6/GONG 98 Workshop organizing committee for providing the financial support.

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