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Study of Sun's rotation and solar activity

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Abstract. In my thesis I have presented many interesting properties of Sun's rotation and magnetic activity derived from extensive analysis of over 100 year photoheliographic data on sunspot activity and 26 year's data on photospheric motions from Mt Wilson, and supporting data from GONG and SOHO. Some important results are :

1. The rate of emergence of toroidal magnetic flux above Sun's surface can be expressed as the superposition of at least four 'global' MHD oscillations. Frequency of the dominant mode is $\approx 1/21.4$ yr^{-1}.

2. There exists a $\sim$ 22 year periodicity in the differential rotation. Thus, the above-mentioned oscillations may be "torsional MHD oscillations".

3. (i) The magnetic structures which yield spot groups with life spans 10–12 days are initially anchored near the base of the convective envelope; (ii) in latitudes $10^o - 20^o$ these structures rise at a rate $\sim$ 21 Mm per day, as the spot group ages; and (iii) the magnetic structures of spot groups which live successively shorter by 1 day are initially anchored in layers successively shallower by $\sim$ 21 Mm.

4. (i) Magnetic structures with magnetic flux $\Phi \geq 10^{22}$ Mx might be generated around the base of the convection zone, (ii) many of the magnetic structures may be fragmenting (or branching) into smaller structures while rising through the solar convection zone, and (iii) magnetic structures with $\Phi < 10^{22}$ Mx might be the fragmented (or branched) parts of the larger magnetic structures.

5. The mean rotation frequencies of the long-lived young groups, the long-lived old groups and the short-lived spot groups suggest that the periodicities

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$\sim$ 21 yr and $\sim$ 11 yr in the differential rotation are dominant in the rotational perturbations of the Sun's deeper layers ($r \sim 0.73 R_\odot$) and shallower layers ($\sim r > 0.95 R_\odot$).

6. The solar meridional flow seems to be strong and poleward during declining ends of the solar cycles. There exists a reasonable correlation between the solar cycle variations of the average meridional motion and the differential rotation, suggesting existence of a coupling in the latitudinal and longitudinal motions somewhere in the convection zone.

Keywords : Sun: rotation–differential rotation–solar activity

1. Introduction

The mechanism of solar activity has been investigated both from theoretical and observational points of view by many authors. It has been generally accepted that interactions of Sun's convection, rotation and magnetic field play a basic role in the generation of solar activity and solar cycle. However, the details of such an interaction are not yet fully understood (see Rosner and Weiss 1992, and references therein).

Greenwich Photoheliographic Results (GPR) give a long data-base for the studies of solar activity, solar cycle, solar rotation and other properties of the motions in the solar convection zone. This data-base has been used for these studies by many authors for a long time. A magnetic tape of Greenwich Photoheliographic Results (GPR) of sunspot group data during 1874–1976 was kindly provided to us by Dr. H. Balthasar. Recently, the upgraded GPR data (1874–1976) and NOAA/UASF data (1977–1981) became available to us. These data were compiled by the National Geophysical Data Center, USA. The spot group data included the observation time (the date and the fraction of the day), heliographic latitude (λ) and longitude (L), corrected whole spot area A (in millionth of a hemisphere) and central meridian distance (CMD), etc., for each day of observation. In my thesis I present studies of solar rotation, solar meridional flow and solar activity from the analysis of the 108 sunspot group data and 26 yr Mt. Wilson velocity data (1967–1994). These studies give some interesting and potentially important clues for understanding the physical processes responsible for the solar activity and the solar cycle phenomena. In Sections 2 to 7 I have summarized the results in my thesis.

2. Legendre-Fourier analysis of magnetic field inferred from sunspot groups

For each time interval (T1, T2) chosen for the analysis (e.g., a sunspot cycle or a sequence of years/cycles) we have defined the *'sunspot occurrence probability'*, $p(\mu, \phi, \tau)$, as

$$p(\mu,\phi,\tau) = \begin{vmatrix} \frac{1}{N}\delta(\mu-\mu_i,\phi-\phi_i,\tau-\tau_i) & \text{at } (\mu_i,\phi_i,\tau_i),\ \text{i} = 1, 2, ..., \text{N}, \\ 0 & \text{elsewhere in } (\mu,\phi,\tau) \text{ space.} \end{vmatrix}$$

where $\tau = (t - T_1)/(T_2 - T_1)$, $\mu = cos\theta$, $\theta = 90^\circ - \lambda$, δ represents a delta function in (μ,ϕ,τ), $N = N(T_1, T_2)$ is the number of data points during the interval (T_1, T_2) and t is the time of observation from the *zero* hour of the first day of the interval (T_1, T_2).

Using Hale's Law of magnetic polarities we define a *'nominal toroidal magnetic field'*, $B_\phi(\theta,t)$, as

$$B_\phi(\theta,t) = \begin{vmatrix} \pm p(\theta,t) & \text{in the northern wings of the "butterfly diagrams"} \\ \mp p(\theta,t) & \text{in the southern wings of the "butterfly diagrams".} \end{vmatrix}$$

In each case, the upper sign is for data from the 'even numbered' sunspot cycles and the lower one is for data from the 'odd numbered' cycles. We did Legendre-Fourier (L-F) analysis of $B_\phi(\theta,t)$.

We identified the following four modes of coherent global oscillations with frequency $\nu_* = 1/21.4\ \text{yr}^{-1}$:

$$B_1 = \left[\sum_{l=1}^{11} a_l P_l(\mu)\right] sin(2\pi\nu_* t), \quad B_2 = \left[\sum_{l=3}^{17} b_l P_l(\mu)\right] cos(2\pi\nu_* t),$$

$$B_3 = \left[\sum_{l=15}^{29} a_l P_l(\mu)\right] sin(2\pi\nu_* t), \quad B_4 = \left[\sum_{l=21}^{25} b_l P_l(\mu)\right] cos(2\pi\nu_* t),$$

where a_l and b_l are coefficients determined by the L-F analysis.

Though the sunspot data came only from latitudes $< 35^\circ$, we found that the superposition of B_1, B_2, B_3 and B_4 not only ***reproduces*** the butterfly diagrams, but also ***predicts*** the following large scale characteristics of the weak fields in latitudes $> 35^\circ$: (i) the migrations of neutral lines from latitudes $\sim 35^\circ$ *up to* $\sim 90^\circ$, and (ii) polar field reversals at the correct phase of the cycle. This suggests that the buoyant toroidal magnetic flux tubes, whose emergence above the Sun's surface produces 'sunspot' activity as well as the 'quiet sun' activity, may be created in the Sun by interference of 'global' MHD oscillations/waves represented by the dominant L-F terms. The structure of the L-F spectrum of these oscillations/waves and its approximate 'steadiness' suggest that these oscillations are resonating with frequencies forced by some long-lived sources of excitation (Gokhale et al. 1992; Gokhale and Javaraiah 1992, 1995).

3. Periodicities in the Sun's surface rotation

Sun's differential rotation can be determined from full disc velocity data using the 'standard' polynomial expansion: $\omega(\lambda) = A + B\sin^2\lambda + C\sin^4\lambda$, while for sunspot data, it is sufficient to use only the first two terms of the expansion: $\omega(\lambda) = A + B\sin^2\lambda$, where $\omega(\lambda)$ is the solar rotation rate at latitude λ, the parameter A represents the equatorial or 'mean' rotation rate, B and C measure the latitude gradient of the rotation rate with B representing mainly low latitudes and C representing largely higher latitudes.

Snodgrass & Howard (1985) used the so-called Gegenbauer Polynomials as a set of disk-orthogonal fit functions with $T_1^0(\sin\lambda) = 1$, $T_2^1(\sin\lambda) = 5\ \sin^2\lambda - 1$, and $T_4^1(\sin\lambda) = 21\sin^4\lambda - 14\sin^2\lambda + 1$, which leads to the following expansion:

$$\omega(\lambda) = \bar{A} + \bar{B}(5\sin^2\lambda - 1) + \bar{C}(21\sin^4\lambda - 14\sin^2\lambda + 1).$$

The coefficients $\bar{A}$, $\bar{B}$, and $\bar{C}$ are free of crosstalk (Snodgrass 1984); $\bar{A}$ represents the 'rigid body' (or 'mean') component in the rotation, $\bar{B}$ and $\bar{C}$ are the components of the differential rotation. If the polynomial expansion is terminated at $\bar{C}$ (or C), the coefficients, $\bar{A}$, $\bar{B}$, and $\bar{C}$, are related to the standard A, B, and C coefficients as follows:

$$\bar{A} = A + (1/5)B + (3/35)C, \quad \bar{B} = (1/5)B + (2/15)C, \quad \bar{C} = (1/21)C.$$

In this case, the temporal variation of $\bar{C}$ is identical to that of C.

We studied periodicities in the differential rotation from power spectrum analysis of the differential rotation coefficients derived from the 103 yr GPR sunspot group data and 26 yr Mt. Wilson velocity data (1969–1994). We computed the values of the differential rotation coefficients from sunspot group data. We have used the values of the differential rotation coefficients A, B, C derived from the Mt. Wilson velocity data. These values were kindly provided by Dr. R. F. Howard. We focus on the Mt. Wilson velocity data obtained after 1981 with reduced instrumental noise.

In the photospheric 'mean rotation' $\bar{A}$, determined from the Mt. Wilson velocity data during 1982–1994, we found the periods: 6.7–4.4 yr, 2.2 ± 0.4 yr, 1.2 ± 0.2 yr, and 243 ± 10 day (with a $\geq 99.9\%$ confidence level), which are similar to the known periods in other indicators of solar activity suggesting that they are of solar origin. The 11-yr periodicity is found to be insignificant or absent in $\bar{A}$. In the differential rotation parameters $\bar{B}$ and $\bar{C}$, determined from the same data set, we found only the ~ 11 yr period with a $\geq 99.9\%$ confidence level.

The time series of $\bar{A}$ determined from the yearly sunspot group data obtained during 1879–1976 is found to be similar to the corresponding time series of $\bar{B}$. After correcting for data with large error bars (occurring during cycle minima), we have found periods of 18.3 ± 3.0 yr and 7.5 ± 0.5 yr in $\bar{A}$ and these and a few other short periods (e.g., 3.0 ± 0.1 yr, etc.) in $\bar{B}$.

We found considerable differences in the periodicities of $\bar{A}$ and $\bar{B}$ determined from the velocity data and those determined from the spot group data. Presence of these differences may be understood if the rotation rates determined from sunspot data represent the rotation rates of the Sun's deeper layers (Javaraiah and Gokhale 1995, Javaraiah and Komm 1999).

4. Periodicities in the north-south asymmetry of the Sun's surface rotation

The North-South (N–S) asymmetry (Xa) of a measure of a solar phenomenon X can be defined as $Xa = (Xn - Xs)/(Xn + Xs)$, where Xn and Xs are the measures of X in the northern and southern hemispheres respectively. Using this formula we calculated the N–S asymmetries, $\bar{A}a$, $\bar{B}a$ and $\bar{C}a$, of the coefficients $\bar{A}$, $\bar{B}$ and $\bar{C}$ and computed FFT power spectra of $\bar{A}a$, $\bar{B}a$ and $\bar{C}a$. In the $\bar{A}a$ and also that of $\bar{B}a$ determined from the spot group data we have detected the periodicities : 45 ±11.5 yr, 21.3 ± 4.5 yr, 13.3 ± 1.5 yr and 10.5 ± 0.5 yr. We have also found similar periodicities in the N–S asymmetry of sunspot activity (Javaraiah and Gokhale 1997a). I have also studied periodicities in N-S asymmetries of differential rotation determined from Mt. Wilson velocity data during 1982-1994.

Some of the dominant periodicities of the solar differential rotation and its N-S asymmetry happen to match with periods of configurations of dominant planets (Javaraiah and Gokhale 1995; Javaraiah 1996). Hence, we speculated on the possibility of planetary configurations providing the perturbations needed for the 'torsional MHD oscillations'. However, within Newtonian mechanics the planetary perturbations are quantitatively quite small. Hence, the role of the solar system dynamics in the basic mechanism of solar activity is still a matter of speculation.

5. Depths of initial anchoring and rising-rate of sunspot magnetic structures

Using Greenwich data on sunspot groups during 1874–1939 we studied the dependence of mean rotation frequency of a spot group on its age (t) and the dependence of the 'initial rotation frequency' of a spot group on its life span (τ). These were compared with the dependence of plasma rotation frequency ($\Omega(r, \lambda)$) on the radial distance (r) and latitude (λ) as determined from helioseismology. From this we obtained the following relations, (Javaraiah and Gokhale 1997b):

$$r(t) = (480.6 \pm 0.7) + (20.9 \pm 0.1)t \quad (1)$$

for the spot groups of life spans 10–12 days in latitude 10°–20°; and

$$r_0(\tau) = (696.5 \pm 0.6) - (20.9 \pm 0.1)\tau \quad (2)$$

for the spot groups of life spans 2–12 days in the entire sunspot latitude belt. Here $r(t)$ and $r_0(\tau)$ are in Mm and the $r_0(\tau)$ represents the 'initial anchoring' depths of the magnetic structure (flux ropes) of spot groups of life span τ. These relations imply the following possibility: (i) the magnetic structures which yield spot groups with life spans 10–12 days are initially anchored near the base of the convective envelope; (ii) in latitudes $10^o - 20^o$ these structures rise at a rate $\sim$ 21 Mm per day, as the spot group ages; and (iii) the magnetic structures of spot groups which live successively shorter by 1 day are also initially anchored in layers successively shallower by $\sim$ 21 Mm.

The magnitudes of slopes in the equations (1) and (2) are equal. It follows that for spot groups with $\tau \leq 9.5$ days

$$r_0(\tau) \approx r(10.5 - \tau). \tag{3}$$

This means that in latitudes $10° - 20°$ the 'initial anchoring' r_0 of the magnetic structures of spot groups with $\tau \leq 9.5$ days is at the depth r where the anchoring of the magnetic structures of spot groups with life span $\tau = 10.5$ days reaches at the age of $t = (10.5 - \tau)$ days.

We analyzed the upgraded Greenwich data of 1874–1976. The relation (1) above, is found to be more realistic for spot groups with average area $A \geq 130$ millionth of the solar hemisphere (corresponding magnetic flux, $\Phi \geq 10^{22}$ Mx). For spot groups of life span 2–12 days we found the following relations between their number N, average area A and life span τ:

$$A(\tau) = 15.24\ exp(\tau/4.48) \tag{4}$$

and

$$N(\tau) \sim 2824\ exp(-\tau/5.38). \tag{5}$$

Equations (2), (3) and (4) imply the exponential relation :

$$A \approx 130\ exp(-H/95), \tag{6}$$

where H in Mm, is the anchoring height above the base of the convection zone. From these two facts we have drawn the following tentative inferences: (a) magnetic structures with $\Phi \geq 10^{22}$ Mx might be generated around base of the convection zone, (b) many of the magnetic structures may be fragmenting (or branching) into smaller structures while rising through the solar convection zone, and (c) magnetic structures with $\Phi < 10^{22}$ Mx might be the fragmented (or branched) parts of the larger magnetic structures. These inferences are consistent with the proposals of some theoretical models (e.g., Parker 1979).

6. Confirmation of 22-year variation in the solar differential rotation and its depth

Using the upgraded GPR sunspot group data during the whole period 1879–1975 we found the equatorial rotation rate A is significantly larger in the odd numbered solar cycles (ONSCs) than in the even numbered solar cycles (ENSCs). The N–S asymmetry in A seems to be large in the ONSCs and less in the ENSCs. The rotation is significantly more differential in the ONSCs than in the ENSCs and the difference is mainly contributed from the southern hemisphere. In the northern hemisphere the difference is marginal. N–S asymmetry in B is significant in the ENSCs and it is not significant in ONSCs. In ENSCs the rotation is more differential in the northern hemisphere than in the southern hemisphere and it is in opposite sense in the ONSCs (see also Javaraiah 2002).

The coefficient A varies significantly only during ONSCs with amplitude ~ 0.01 $\mu\, rad\ s^{-1}$, at minimum years. There exists a good anticorrelation between the variations of B derived from the ONSCs and ENSCs, suggesting existence of a '22-yr' periodicity in B. The amplitude of variation of B is $\sim 0.05\ \mu\, rad\ s^{-1}$ (Javaraiah 2000).

In the differential rotation coefficient B, '22-yr' periodicity is dominant if the B is determined from the long–lived young spot groups, where as '11-yr periodicity is dominant if it is determined from the long–lived old groups or from the short lived groups. From comparing the mean rotation frequencies of the young, the old and the short lived spot groups with the $\Omega(r, \lambda)$ 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 ($r \sim 0.73R_\odot$) and shallower layers ($\sim\ r > 0.95R_\odot$), respectively (Javaraiah 1998).

7. Variation of the Sun's meridional flow during the solar cycle

Using the GPR sunspot group data during 1874–1976 we found the following results, (Javaraiah 1999): In the latitude interval $20^o - 30^o$, the forms of 'initial' meridional motion, $v_{ini}(\tau)$, of sunspot groups and mean meridional motion, $v(t)$, are largely systematic and mutually similar in both north and south hemispheres. In $v(t)$ there is a suggestion of existence of periodic variation in the meridional motion with period 4-day and amplitude 10–20 m s^{-1}. The meridional flows ($v_e(t)$) determined from the data during the last few days of spot groups of life spans 10–12 days are found to have magnitudes and directions similar to those of the surface meridional plasma flows determined from Dopplergrams and magnetograms. Existence of N–S asymmetry in $v_e(t)$ is suggested. Using the anchoring depths of magnetic structures for spot groups of different life spans (τ) and age (t) estimated by us, I suggest that the patterns of $v_{ini}(\tau)$ and $v(t)$ may represent the spatial structure of the meridional flow in the Sun's convection zone, rather than its temporal variation. The mean meridional motion (v') of sunspot groups seems to vary with the phase of the solar cycle. The velocity is not significantly different from zero during the rising phase of the cycle and there is a suggestion of poleward motion (a few m s^{-1} at lower latitude and ~ 15 m s^{-1} at higher latitudes) during the declining end of the cycle. Existence of N–S asymmetry in the solar cycle dependence of the mean meridional motion of sunspot groups is suggested. The strength of the asymmetry depends on the phase of the cycle. On the average, during $\frac{3}{4}$ of the cycle, the velocity seems to be poleward in the southern hemisphere and equatorward in the northern hemisphere. There exists a reasonable correlation between the solar cycle variation of the average meridional motion v' and that of A, between v' and B, and between v' and $\tilde{A}$, suggesting existence of coupling in the latitudinal and longitudinal motions, somewhere in the convection zone.

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