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Sunspot Groups as Tracers of Sub-Surface Processes

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Abstract. Data on sunspot groups have been quite useful for obtaining clues to several processes on global and local scales within the sun which lead to emergence of toroidal magnetic flux above the sun's surface. I present here a report on such studies carried out at Indian Institute of Astrophysics during the last decade or so.

Key words. Sunspot group—solar cycle—solar rotation.

1. Introduction

Locations and epochs of sunspot groups can be specified much less accurately than those of individual sunspots. However, sunspot groups provide measures of toroidal magnetic flux emerging at the locations and epochs of their occurrence. Because of this the data on sunspot groups have been more useful than the data on individual sunspots, in studies of several sub-surface processes leading to emergence of toroidal magnetic flux above the sun's surface. Extensive studies of sunspot cycle, its north-south symmetry (and small but significant asymmetry), its distribution on sun's surface and in time, sun's rotation, meridional motions of sunspots, etc., have been carried out by several authors using data on sunspot groups ever since such data have been available. Compilation of Greenwich ledgers of data on sunspot groups during 1874–1976 by Balthasar and Wöhl on magnetic tapes led to a large number of such studies during 1980's, especially of sun's differential rotation (Balthasar & Wöhl 1980; Balthasar *et al.* 1986; Zappalá & Zuccarello 1991 and references therein). Owing to shortage of time I restrict this review to present a report on the work done by our group at Indian Institute of Astrophysics which fits the title of this colloquium and the title of my talk. I shall point out the clues given by these studies for modeling the cyclical evolution of solar magnetic fields, but I shall not report on the follow-up work which is incomplete.

2. Solar magnetic cycle as global MHD oscillations

Using lifespan of a sunspot group as a measure of toroidal magnetic flux emerging during its life, and attaching to it the sign of polarity of bipolar magnetic regions in the respective wing of the butterfly diagram, Gokhale *et al.* (1992) determined the rate, $\dot{\Phi}$, of emergence of toroidal magnetic flux as a function of heliographic co-latitude θ and time t. Legendre-Fourier (LF) analysis of $\dot{\Phi}(\theta, t)$ using Greenwich data during 1874–1976 showed (Gokhale & Javaraiah 1992) that it can be expressed as superposition of at least *four* ‘global’ oscillations described by:

$$\dot{\Phi}(\theta, t) = \dot{\Phi}_{0s} + \dot{\Phi}_{0c} + \dot{\Phi}_{1s} + \dot{\Phi}_{1c} + \cdots, \qquad (1)$$

where

$$\dot{\Phi}_{0s} = [\Sigma_{l=1,3,\ldots 13} A_s(0, l) P_l(\theta)] \sin(2\pi\nu_0 t), \qquad (2a)$$

$$\dot{\Phi}_{0c} = [\Sigma_{l=3,5,\ldots 17} A_c(0, l) P_l(\theta)] \cos(2\pi\nu_0 t), \qquad (2b)$$

$$\dot{\Phi}_{1s} = [\Sigma_{l=15,17,\ldots 29} A_s(1, l) P_l(\theta)] \sin(2\pi\nu_1 t), \qquad (2c)$$

$$\dot{\Phi}_{1c} = [\Sigma_{l=19,21,23,25} A_c(1, l) P_l(\theta)] \cos(2\pi\nu_1 t), \qquad (2d)$$

where $P_l(\theta)$ represent Legendre polynomials of order l in $\cos(\theta)$, ‘$A_s(0, l)$’, etc., are coefficients of the respective LF terms determined by the analysis, and

$$\nu_0 = 1/21.6\,\mathrm{yr}^{-1}, \quad \nu_1 = 1/7\,\mathrm{yr}^{-1}.$$

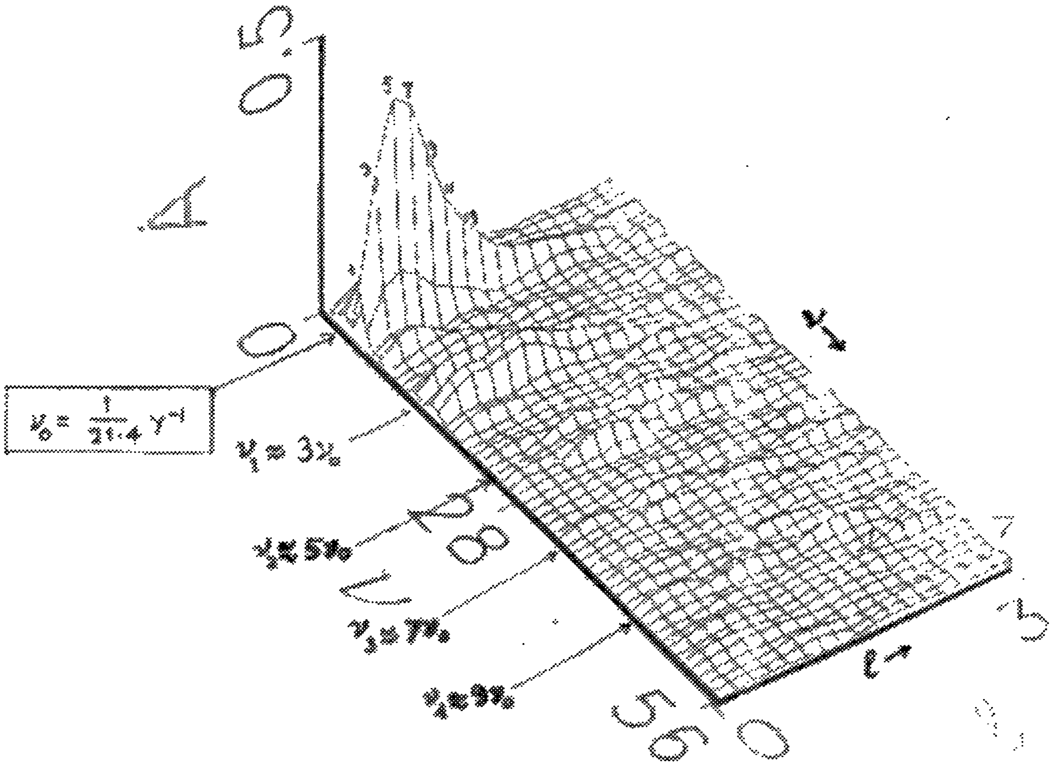

Figure 1. Legendre-Fourier spectrum of $\dot{\Phi}_{(}\theta, t)$ during 1874–1976.

Each sum on the right side of equation (1) corresponds to a distinct and significant hump in the LF power spectrum (Fig. 1). The LF power in terms of l = even is much less though not insignificant. Further studies revealed the following facts:

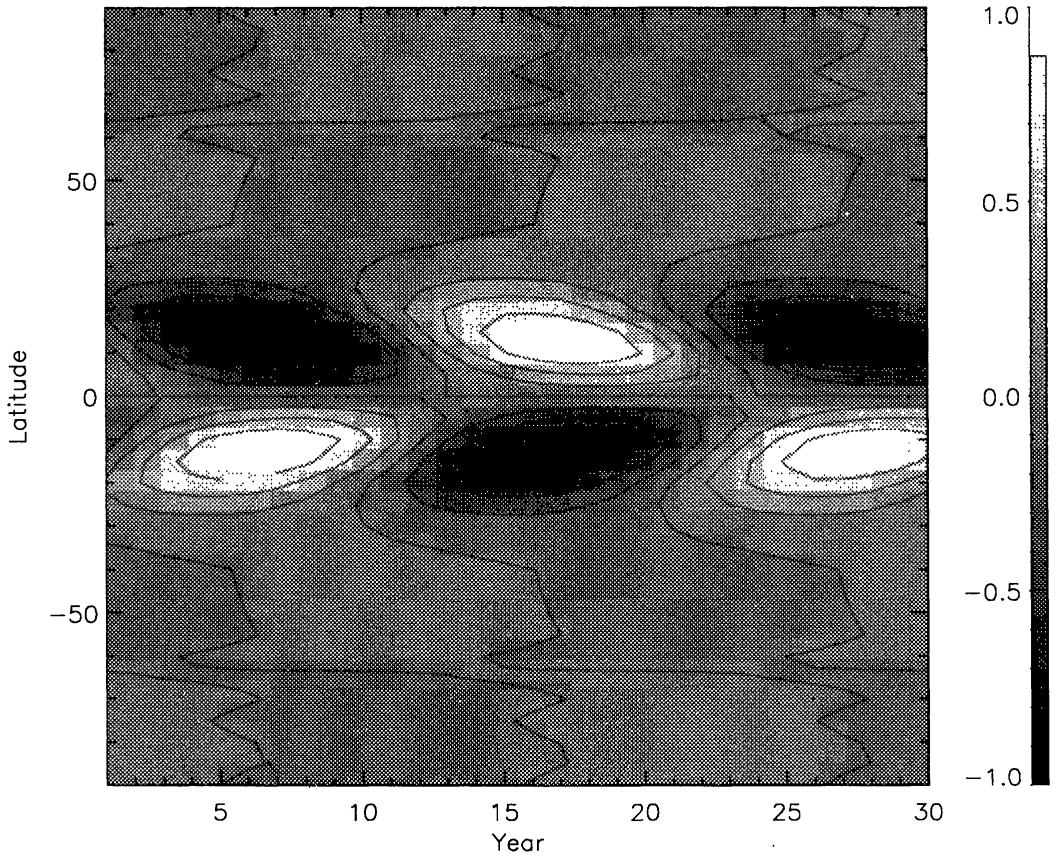

Figure 2. $\dot{\Phi}(\theta, t)$ given by sum of first four terms in equation (1). Numbers on the horizontal axis represent years. Different shades represent values of $\dot{\Phi}$ in an arbitrary unit. Continuous lines represent contour levels. Zero level contours migrate to poles.

- The relative amplitudes and relative phases of LF terms in each sum and those of terms in one sum to another, are nearly independent of the length and location of the sampled time interval, provided it is longer than 11 years.
- The relative amplitudes and phases of LF terms in $\dot{\Phi}_{0s}$ (the most dominant terms) are similar to those given by the *magnetogram* data during 1960–1985 (Stenflo 1988).
- Superposition of first four terms in equation (1) not only *reproduces* the 'butterfly diagrams', but also *predicts*: (i) migrations of 'weak' field and 'neutral lines' from "middle" latitudes to poles, and (ii) reversal of "polar" fields at appropriate phase in the cycle, *though the analysed data come only from the "low" latitudes*. (Fig. 2). (See Gokhale & Javaraiah 1992).
- The magnitude of a sunspot cycle number '*n*' has about 90% correlation to the change in the phase of oscillation $\dot{\Phi}_{0c}$ from cycle number '$n-2$' to cycle number '$n-1$'. This fact can be used to *predict* the magnitude of a *new* sunspot cycle from the analysis of data during *previous two* cycles. (Gokhale & Javaraiah 1995; see Fig. 3).

The above facts strongly indicate that the expressions $\dot{\Phi}_{0s}$, $\dot{\Phi}_{0c}$, $\dot{\Phi}_{1s}$ and $\dot{\Phi}_{1c}$ represent *physically real* global oscillations of the sun. Concentration of LF power in ridges parallel to *l*-axis in Fig. 1 suggests that these oscillations may be 'forced' oscillations.

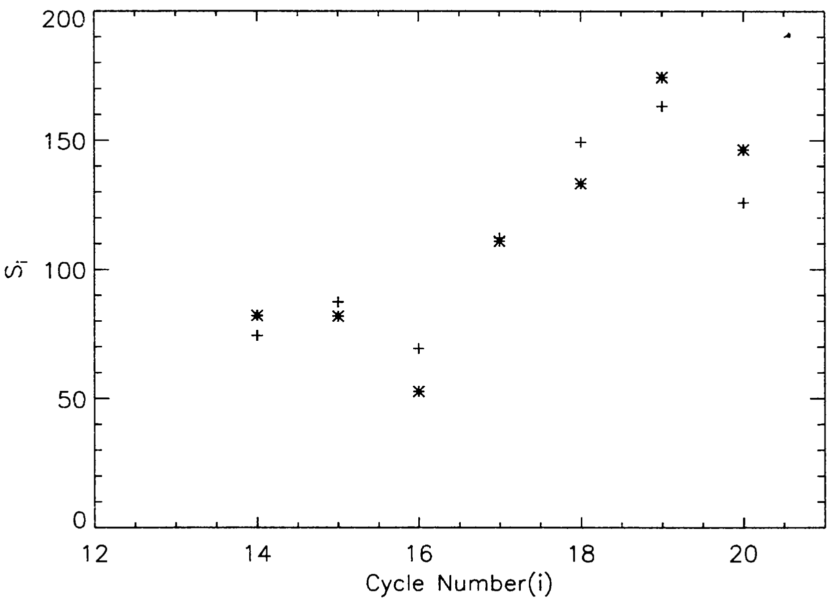

Figure 3. Observed magnitudes S_i of sunspot cycle numbers i compared to those predicted from their 90% correlation to the phase shift of Φ_{0c} from cycle no. '$i-2$' to cycle number '$i-1$'. The observed and the predicted values are represented by '+' and * respectively.

3. 'Torsional nature of the MHD oscillations'

Year-to-year variations of the differential rotation coefficients 'A' and Fourier analysis of the temporal variations of the differential rotation coefficient 'B' computed from longitudinal motions of sunspot groups yield frequencies equal to, within uncertainties, the frequencies ν_0 and ν_1, in the rate of emergence of toroidal magnetic flux (cf. section 2) with high statistical significance (Javaraiah & Gokhale 1995).

This suggests that the four oscillations found in Φ may be "torsional MHD oscillations" of even parity in rotation (odd parity in toroidal field).

4. North-south asymmetry

Several common periodicities exist between the temporal variations of north-south asymmetries in the amount of sunspot activity and in the coefficients of differential rotation. However variations of asymmetries in activity and rotation are *poorly* correlated to one another (Javaraiah & Gokhale 1997a).

5. Initial anchoring and rate of emergence of magnetic structures associated with sunspot groups

From similarity of age and life-span dependencies of spot group rotation rate to the depth dependence of plasma rotation rate it is estimated that

- magnetic structures of spot groups rise at the rate of 21 Mm/day,
- magnetic structures of sunspot groups living less than or equal to 2 days are initially anchored near the Sun's surface,

- those of spot groups with life spans from 2 to 9 days are initially anchored at increasingly larger depths, at the rate of about 21 Mm for each extra day of life span (Javaraiah & Gokhale 1997b).

6. Depth-dependence of 'torsional' periodicity

The dominant periodicity in 'B' determined from 'young' long-lived groups is '21 yr'. That determined from 'old' long-lived groups *and* from 'short-lived' groups is '11 yr'. This result, taken along with the estimated depths of 'initial anchoring' suggests that the '21 yr' periodicity in 'B' is dominant near the base of the convective envelope, and the '11 yr' periodicity is dominant near the surface (Javaraiah 1998).

7. Short term periodicities in differential rotation

Javaraiah & Komm (1999) have found several short term periodicities in the mean photospheric rotation rate $\bar{A}$ determined from Mt. Wilson velocity data during 1869–1994 and similar periodicities from sunspot group data during 1982-1994. However, the sunspot group data during 1874–1976 shows only harmonics of the solar magnetic cycle.

Periodicities of 'A' and 'B' determined from the spot group data differ considerably from those determined from dopplergram data, since sunspot group rotation is affected by plasma rotation sampled over several depths, latitude zones and solar cycle phases. Separated sunspot group samples are often too small to yield significant results.

The coefficient 'A' seems to undergo significant variation of magnitude ~ 0.01 μ rad s^{-1} during *odd* numbered cycles. Variations in 'B', determined from spot groups living 2–12 days and using superposed epoch analysis, are $\sim 0.05\,\mu$ rad s^{-1}, and are during the odd numbered cycles opposite to the variations during the even numbered cycles, which confirms the existence of a 22 yr periodicity in 'B' (Javaraiah 2000, in these proceedings).

8. Meridional flows and their coupling to rotational flows

The meridional flows determined from the data during the last 2–3 days of spot groups living 10–12 days are found to have magnitudes (10–20 m/s) and directions (poleward), similar to those of the surface meridional plasma flows determined from the dopplergrams and magnetograms. This indicates global coupling of meridional and rotational flows (Javaraiah 1999).

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