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Helioseismic Solar Cycle Changes and Splitting Coefficients

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Abstract. Using the GONG data for a period over four years, we have studied the variation of frequencies and splitting coefficients with solar cycle. Frequencies and even-order coefficients are found to change significantly with rising phase of the solar cycle. We also find temporal variations in the rotation rate near the solar surface.

Key words. Solar cycle—rotation—activity.

1. Introduction

With the installation of the GONG instrument in 1995, the network has produced unprecedented amount of *p*-mode frequency data covering the descending phase of solar cycle 22 and the rising phase of cycle 23. These data sets have enabled us to make a detailed analysis of the cyclic variation of the *p*-mode frequency shifts and splitting coefficients. Using the subset of GONG data, Bhatnagar *et al.* (1999) studied the shift in mode frequencies for a period of two years starting from August, 1995 and confirm that the frequencies vary with the level of solar activity.

2. Data sets

The mode frequencies used in this study were estimated from the 3-month power spectra using the standard GONG analysis. The period under study extends from 1995 May 7th to 1999 August 1st. The data were divided into 41 overlapping time series with start dates spaced by 36 days (GONG months 2-42) and contains *m*-averaged *p*-mode multiplets in the frequency range of 1.5 mHz to 3.5 mHz and $\ell_{max} = 150$. The mode frequencies are defined by

$$\nu_{n,\ell,m} = \nu_{n,\ell} + L \sum_{s=1}^{m} a_s^{n,\ell} P_s(m/L), \quad (1)$$

where $a_{s,n,l}$ are the splitting coefficients and $L^2 = \ell(\ell+1)$.The remaining symbols have their usual meanings.

3. Analysis and results

The temporal evolution of the frequency shifts over the period of four years is shown in Fig. 1. In the same figure, we also show the activity indices represented by means

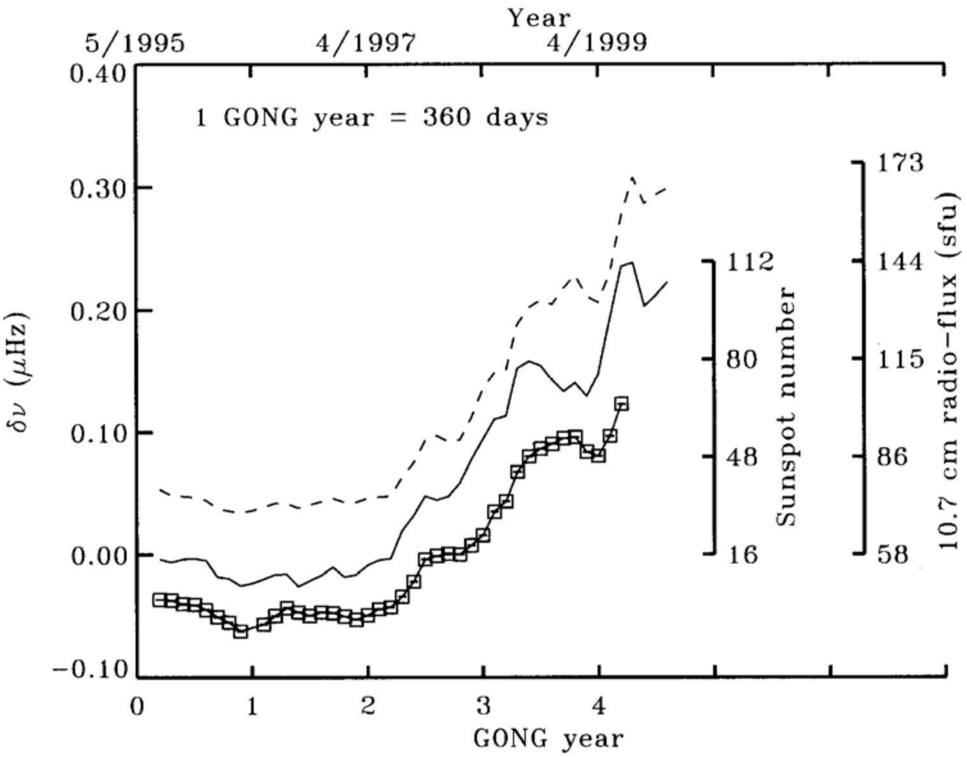

Figure 1. The temporal evolution of frequency shifts over a period of four years is shown by the solid line with squares. The solid and dashed lines represent the scaled mean sunspot number and 10.7 cm radio flux.

of sunspot number (R_I) and 10.7 cm radio flux (F_{10}). It is noted that the frequency shifts follow the trend of solar cycle. The regression analysis between the shifts and the activity indices shows a strong linear correlation with correlation coefficients of 0.99.

It is known that the solar differential rotation and other symmetric breaking factors like magnetic field can lift the degeneracy of the solar acoustic modes and split the eigen frequencies as defined in equation (1). The solar cycle variation of the even order splitting coefficients are shown in Fig. 2. We find that a_2 has a strong correlation with activity while a_4, a_6, and a_8 coefficients are anti-correlated. Howe *et al.* (1999) also investigated the temporal behaviour of these coefficients at 3 mHz and had obtained similar results.

The odd-order splitting coefficients measure the solar rotation. The variation of solar rotation rate with depth and latitude is studied by using analytical methods proposed by Morrow (1988). In an asymptotic limit, the appropriate combination of odd order coefficients reflects the depth variation of the angular velocity at a chosen co-latitude, ϕ (= 90° — θ, where θ is latitude).

$$\Omega^{nl}(\phi) \approx \sum_{i=0}^{s_{\max}} d_{2i+1}(\phi) a_{2i+1}^{nl}, \tag{2}$$

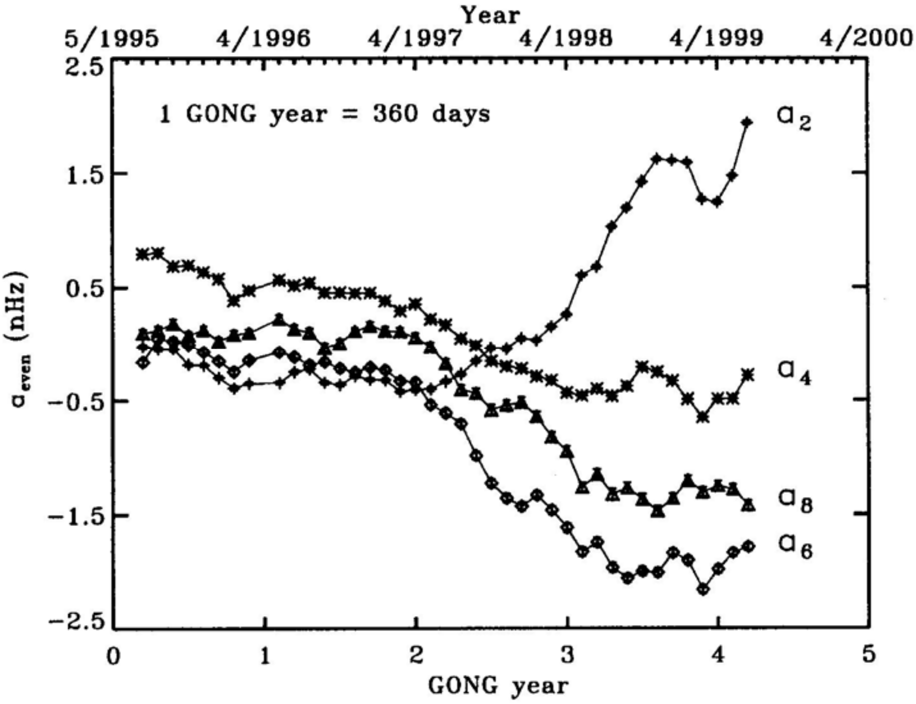

Figure 2. The temporal evolution of even order splitting coefficients.

where

$$d_1 = 1, \tag{3}$$

$$d_3 = [1 - 5\cos^2\phi], \tag{4}$$

$$d_5 = [1 - 14\cos^2\phi + 21\cos^4\phi], \tag{5}$$

$$d_7 = [1 - 27\cos^2\phi + 99\cos^4\phi - \frac{429}{5}\cos^6\phi], \tag{6}$$

$$d_9 = [1 - 44\cos^2\phi + 286\cos^4\phi - 572\cos^6\phi - \frac{2431}{7}\cos^8\phi]. \tag{7}$$

In the earlier studies (Mirror (1988; Jain *et al.* 2000), the summation in equation (2) was terminated by setting $s_{max} = 2$. With the availability of higher order coefficients in GONG data, the summation is extended to $s_{max} = 4$ (terms involving a_9^{nl}). The corresponding rotation rate at equator is given by

$$\Omega^{nl}(90°) \approx a_1^{nl} + a_3^{nl} + a_5^{nl} + a_7^{nl} + a_9^{nl}. \tag{8}$$

In Fig. 3, we show the time variation of rotation rate for four different latitudes near the surface i.e. $\nu/L = 30$. A small but significant change in rotation rate of the order of 3 nHz over a period of more than four years is clearly seen. These changes have been interpreted in terms of zonal flows earlier seen in BBSO data for cycle 22 (Woodard & Libbrecht 1993) and Doppler measurements (Howard & LaBonte 1980). Recently using inversion techniques, Basu & Antia (1999) have also found a systematic zonal flow migrating towards lower latitudes during the rising phase of cycle 23.

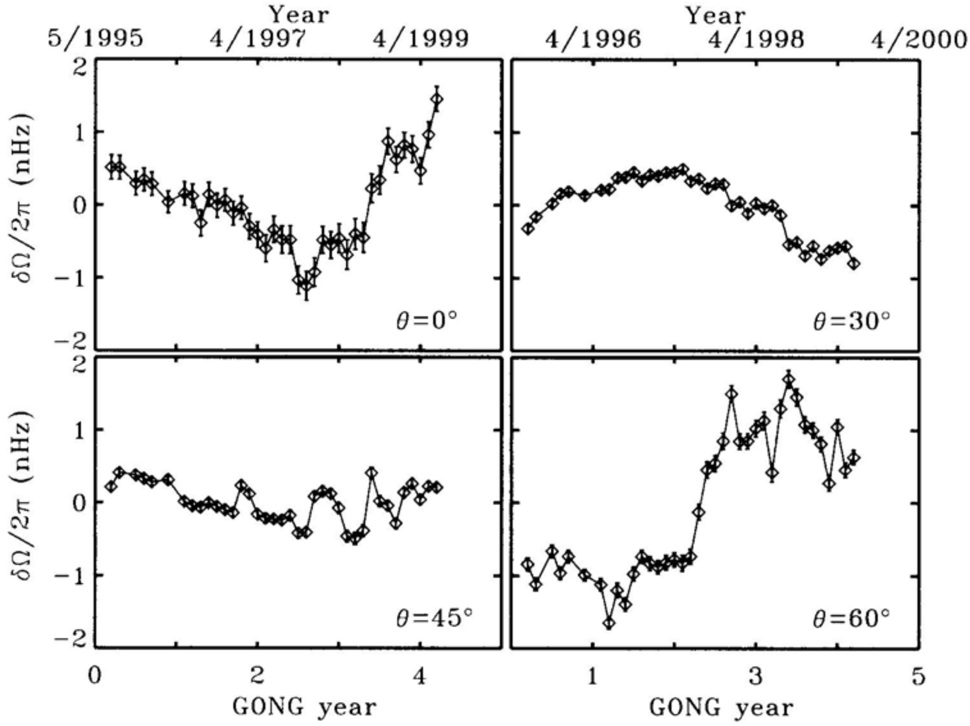

Figure 3. The temporal evolution of solar rotation rate as a function of GONG year (1 GONG year = 360 days) for different latitudes.

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