

Solar-cycle variation of oscillation frequencies and surface magnetic field



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Abstract

In this project I investigate the relationship between solar oscillation frequencies and surface magnetic fields over the course of the last solar cycle. Using MDI and GONG data, I study the variation in the even frequency-splitting coefficients a_k (describing solar asphericity and effects of the magnetic field), and the variation in the coefficients B_k of the latitudinal Legendre decomposition of the surface magnetic field, during the period 1996 - 2010. I find a strong linear correlation between the a_k and B_k coefficients, during both the rising and declining phases of the solar cycle, consistent with results published in 2001 (Antia et al. [1]). I also investigated different ways to handle the magnetic field decomposition at the poles, and find that the linear correlation persists, though with varying intercepts. The variation of slope with coefficient index that I find is non-monotonic, which disagrees with the previous study by Antia et al.

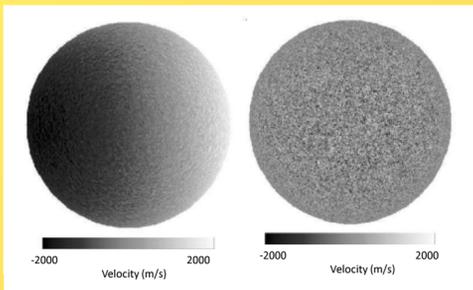


Figure 1: Doppler image of the solar surface (left). After subtracting rotation (right), we can see the fine structure of oscillations on the surface, allowing us to deduce conditions in the solar interior. Reproduced from Christensen-Dalsgaard [2].

Oscillation modes

The Sun does not merely pulsate in a spherically symmetric manner. The waves in the Sun interfere to form standing waves, of which there are many modes. Each mode is characterised by three numbers (Fig. 2).

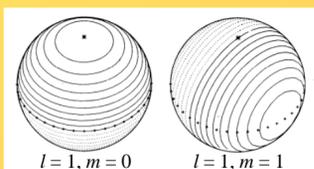
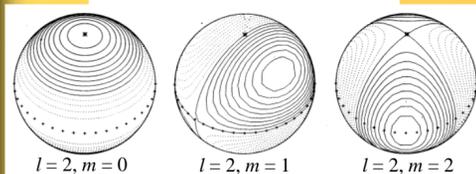


Figure 2: The radial order n counts the number of nodes in the radial direction. The degree l and azimuthal order m characterise the surface configuration of oscillation



modes. The displacement on the surface can be described by spherical harmonics Y_l^m which are shown here for various values of l and m . Reproduced from Christensen-Dalsgaard [3].

Frequency Splitting Coefficients

For a perfectly spherically symmetric Sun, modes of the same n and l , but different m , are degenerate in frequency. In actuality, there is a frequency splitting which can be expressed as a sum of orthogonal Legendre-like functions:

$$v_{nlm} = v_{nl0} + \sum_{k=1}^{k_{max}} a_k(n, l) P_k^{(l)}(m)$$

The odd a_k -coefficients ($k = 1, 3, 5, \dots$) reflect frequency differences due to rotation, while the even coefficients are due to equatorial bulging and the solar magnetic field.

Data

- SOHO spacecraft - Michelson Doppler Interferometer (MDI)
- Global Oscillation Network Group - 6 ground-based observation stations

Oscillation frequency data was collected over chunks of 72 days (SOHO) or 36 days (GONG) and analysed using Fourier methods to find the average frequency of each mode during that chunk of time.

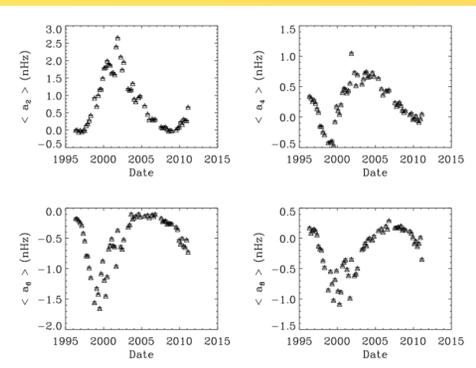


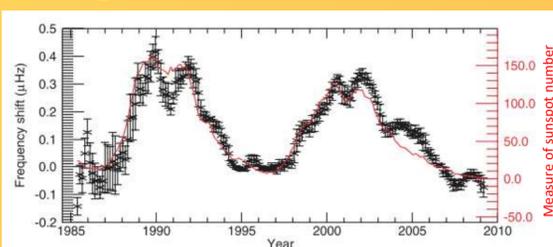
Figure 3: Variation of the first four even coefficients over the solar cycle. The values peak around 2000 (solar maximum), as expected since the surface magnetic field is strongest then.

Comparison with Magnetic Field

In a 2001 paper, Antia et al. [1] found a linear correlation between the a_k coefficients and the coefficients B_k for the latitudinal Legendre decomposition of the surface magnetic flux (over the rising phase of the solar cycle). Other research (Fig. 4) suggested that the same relation might not hold over the declining phase.

Figure 4:

Frequency changes of oscillations (black points) and measure of sunspot number (red line) over the last two solar cycles [4].



There is a deviation during the declining phase of the last cycle. Since the frequency shifts are affected by conditions beneath the surface, while sunspot number is a measure of the surface magnetic field, this indicates that there are processes going on in the interior that are not visible on the surface.

Magnetic Field Decomposition

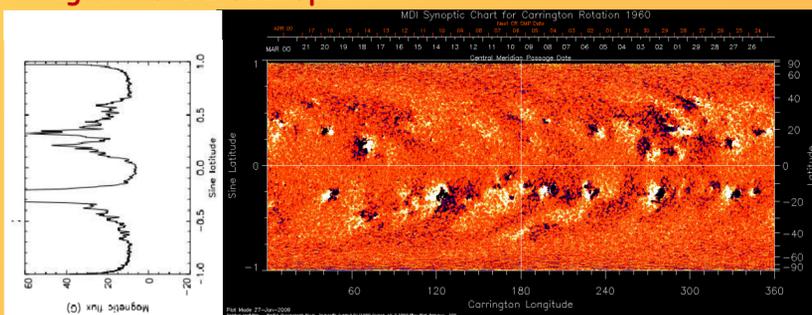


Figure 5: Carrington map of the radial component of the surface magnetic flux, averaged over 27 days (data from the Solar Oscillations Investigation project). The plot on the left shows the azimuthally integrated flux across each latitude.

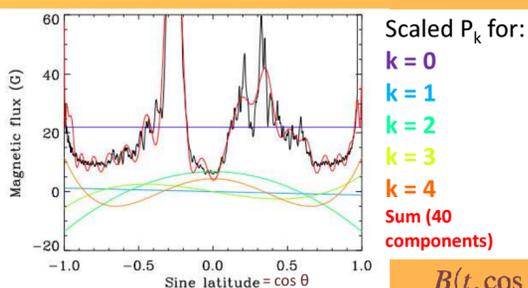


Figure 6: Magnetic field latitudinally decomposed with 40 Legendre polynomials. The B_k coefficients are thus defined:

$$B(t, \cos \theta) = \sum_k B_k(t) P_k(\cos \theta)$$

Coefficient Correlation

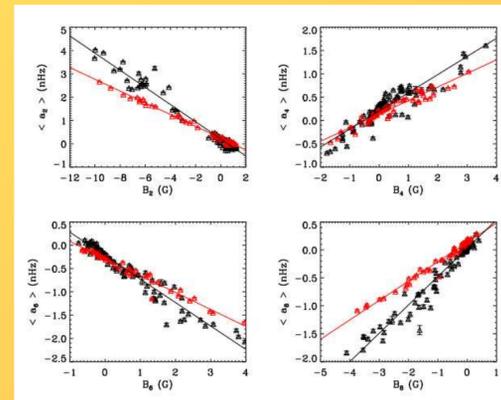


Figure 7: a_k coefficients plotted against B_k coefficients for various values of k , for GONG (black) and SOHO (red) data, showing a strong linear correlation with alternating signs of slope.

Figure 8: The linear relationship holds during both the rising and declining phases, with no particular preference for either phase.

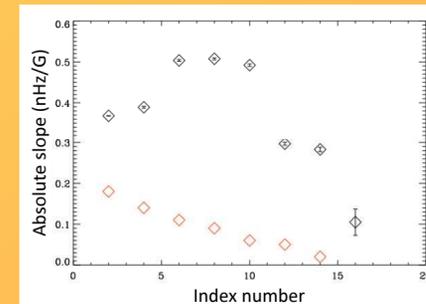
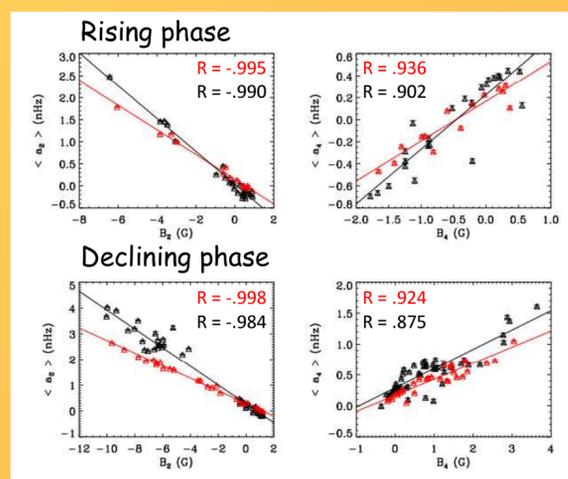


Figure 9: The absolute value of the slope of the linear correlation for GONG data, plotted against index number k (black points). Also shown are the slopes found by Antia et al. [1] (red). My results behave nonmonotonically, unlike Antia's.

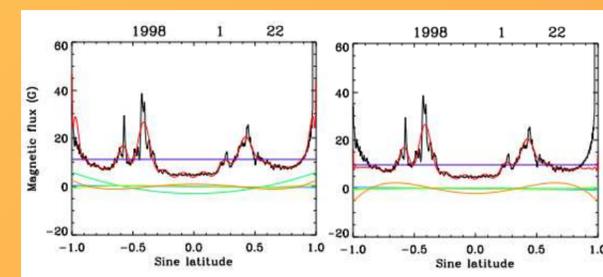
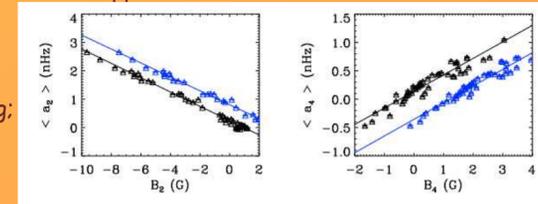


Figure 10: Two different ways of fitting the Legendre functions at the poles. The left method imitates Antia et al., while the right is the method I used to obtain my results (reasoning that the rise in flux near the poles is probably an artificial effect due to projection effects). The difference in the resulting scaling of Legendre polynomials is apparent.

Figure 11: Black - results from imitation of Antia fitting; blue - results from my "flattening" method of fitting.



The linear relation between a_k and B_k persists for all the various methods I tried for Legendre decomposition at the poles, with slopes relatively unaffected.

References

- [1] H. M. Antia, S. Basu, F. Hill, R. Howe, R. W. Komm and J. Schou, *Solar-cycle variation of the sound-speed asphericity from GONG and MDI data 1995-2000*, Monthly Notices of the Royal Astronomical Society **327** (2001), pp. 1029 - 1040
- [2] J. Christensen-Dalsgaard, *Helioseismology*, Reviews of Modern Physics **74** (2003), pp. 1073-1129
- [3] J. Christensen-Dalsgaard, *Lecture notes on stellar oscillations*, fifth edition (2003)
- [4] A. M. Brummhall, W. J. Chaplin, Y. Elsworth, S. T. Fletcher and R. New, *Is the current lack of solar activity only skin deep?*, The Astrophysical Journal **700** (2009), pp. L162 - L165