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Variation of solar oscillation frequencies in solar cycle 23 and their relation to sunspot area and number

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ABSTRACT

Aims. Studying the long term evolution of the solar acoustic oscillations is necessary for understanding how the large-scale solar dynamo operates. In particular, an understanding of the solar cycle variation in the frequencies of solar oscillations can provide a powerful diagnostic tool for constraining various dynamo models. In this work, we report the temporal evolution of solar oscillations for the solar cycle 23, and correlate with solar magnetic activity indices.

Methods. We use solar oscillation frequencies obtained from the Michelson Doppler Imager on board the Solar and Heliospheric Observatory, correlate them with the sunspot number provided by the international sunspot number, $R_{\rm I}$, and compare them with the sunspot number calculated with the Sunspot Tracking And Recognition Algorithm (STARA).

Results. We find that the mean frequency shifts correlate very well with the sunspot numbers obtained from two different datasets. We also find a hysteresis-type behaviour for the STARA sunspot area and mean magnetic field strength for the different phases of the solar cycle. The increase in solar oscillation frequencies precedes slightly the increase in total sunspot area and the mean magnetic field strength for the solar cycle 23. We briefly discuss the cyclic behaviour in the context of p-mode frequencies.

Key words. magnetic fields – Sun: helioseismology – Sun: oscillations – sunspots – Sun: activity

1. Introduction

Helioseismology, the study of solar acoustic oscillations, has enhanced our understanding of the Sun's internal structure and dynamics, from the surface to the deep interior. It has also provided insight into the complex solar magnetism through the study of solar variability appearing in the characteristics of the oscillation mode spectrum. The most obvious manifestation of solar variability is the 11-year cyclic variation of magnetic activity. The 11-year magnetic cycle is believed to be driven by processes located at the base of the convection zone. Using data from solar cycles 21 through 23, it has now been established that the solar f- and p-mode frequencies show high levels of correlation with solar surface activity indicators, the most famous being the number of sunspots on the surface of the Sun (Chaplin et al. 2007; Jain et al. 2009). Such long-term evolution studies of solar oscillations are needed to understand how the large-scale solar dynamo works.

There has been some evidence, however, that the frequency shifts are correlated differently with magnetic and radiative indices (Bachmann & Brown 1993; Bhatnagar et al. 1999). In addition, when the frequency shifts are plotted against a given solar activity with a distinction between the descending and ascending phase, a hysteresis-like curve is observed that is similar to those observed between a pair of activity indices (Bachmann & White 1994). Initially, the hysteresis was observed in case of low-degree modes, where Jimenez-Reyes et al. (1998) showed that the descending phase followed a path slightly higher than the ascending one when the frequency shifts were plotted against the magnetic indices; both the paths were well within the measurement errors for 10.7 cm radio flux or international sunspot number. Subsequently, hysteresis-like effects have been demonstrated for intermediate-degree modes (Tripathy et al. 2001; Jain et al. 2009) for solar cycles 22 and 23. There has been some indication that the hysteresis-like effect seen in the case of low-degree modes can arise owing to the distribution of the magnetic flux with latitude since sectoral and zonal modes have a different sensitivity to magnetic flux at different latitudes (Moreno-Insertis & Solanki 2000).

In this paper we investigate how the solar oscillation frequencies of solar cycle 23 correlate with international sunspot numbers, $R_{\rm I}$[1], and the sunspot number calculated with the Sunspot Tracking And Recognition Algorithm (STARA; see Watson et al. 2011). We also study the correlations of solar oscillation frequencies with sunspot area and their mean magnetic field strengths provided by STARA.

The solar mode frequencies[2] have been obtained by the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SoHO). We use data that consists of 72 non-overlapping sets calculated from time series of 72 days each (see Schou 1999) and which covers the period between 1996 May 1 and 2010 December 1 with two gaps in 1998−1999 due to the breakdown of the satellite. We consider mean frequency shifts and their temporal evolution with other solar cycle parameters such as sunspot number and mean magnetic field strengths. The mean frequency shift, $\delta\nu$, for each data set is obtained as an error-weighted mean where the error corresponds

[1] See http://www.ngdc.noaa.gov
[2] http://quake.stanford.edu/~schou/anavw72z/

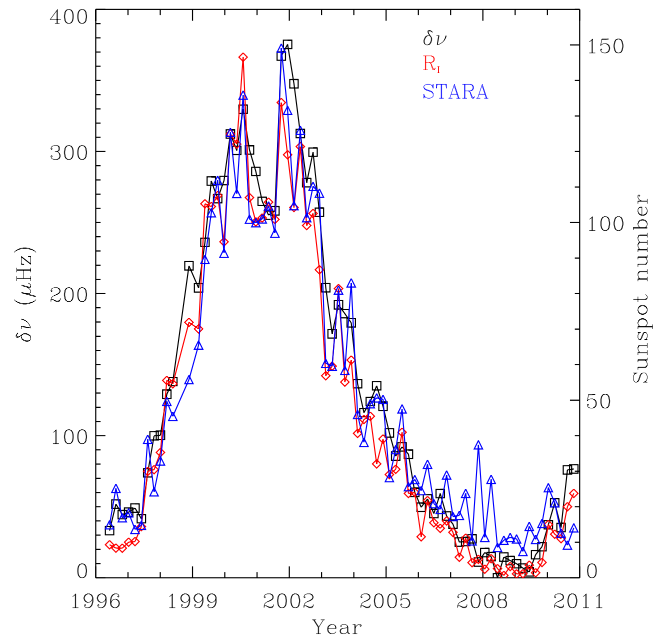

Fig. 1. Averaged p-mode frequency shifts, $\delta\nu$, plotted as a function of year. The red and blue coloured curves are scaled sunspot numbers obtained from international sunspot number ($R_{\rm I}$) and STARA, respectively.

to the formal fitting uncertainties returned by the fitting procedure (Tripathy et al. 2007). We analyse only those modes that are present in all data sets.

Different definitions have been used in the past for calculating frequency shifts (Howe et al. 2002). In this analysis we follow the approach of Woodard et al. (1991) and define the mean frequency shift ($\delta\nu$) as the mode-inertia weighted sum of the measured frequencies:

$$\delta\nu(t) = \sum_{n,\ell} \frac{Q_{nl}}{\sigma^2_{n,\ell}} \delta\nu_{n,\ell}(t) / \sum_{n,\ell} \frac{Q_{n,l}}{\sigma^2_{n,\ell}}, \tag{1}$$

where $\delta\nu_{n,\ell}(t)$ is the change in a given multiplet of n and ℓ, and $Q_{n,\ell}$ is the inertia ratio as defined by Christensen-Dalsgaard & Berthomieu (1991). The parameter $\sigma_{n,\ell}$ is the uncertainty in the frequency measurement.

STARA is a sunspot detection algorithm that uses morphological operators to quickly and accurately track sunspots through optical continuum data. Sunspot detections are then linked to magnetograms to provide magnetic field data on the sunspots. This method involves creating a background image with no sunspots that is then subtracted from the continuum data to leave sunspots intact. It is given in detail in Watson et al. (2009). This study uses the sunspot catalogue created by applying the STARA algorithm to SoHO MDI continuum data, as well as magnetic field information from MDI magnetograms (Watson et al. 2011).

Figure 1 shows the temporal evolution of the frequency shifts. The linearly scaled sunspot number obtained from STARA (blue) and the international sunspot number, $R_{\rm I}$ (red) are also overplotted. The reference frequency is the average value of all the sets, but we have added the minimum frequency shift to all the other frequency shifts to only have positive values. It is clear that the frequency shifts are very well correlated with the sunspot numbers for this solar cycle. The linear correlation coefficients for different phases of the solar cycle are shown in Table 1. We choose ascending phase as years from 1996 to 2000,

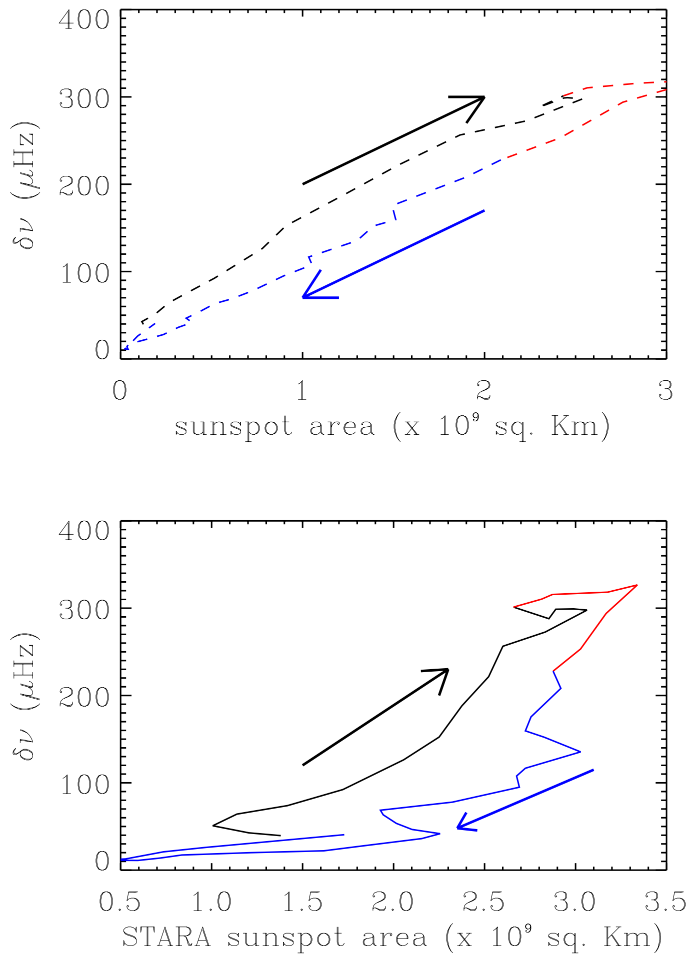

Fig. 2. Averaged p-mode frequency shifts, $\delta\nu$, plotted as a function of total sunspot area provided by USAF/NOAA (*top panel*) and STARA (*bottom panel*). The black, red, and blue colours indicate the ascending, maximum, and descending phases of solar cycle 23, respectively. The arrows indicate the direction of time.

Table 1. Linear correlation coeffs. for different phases of solar cycle 23.

Sunspot No.	Total	Ascending	Maximum	Descending
$R_{\rm I}$	0.97	0.98	0.71	0.98
STARA	0.98	0.96	0.87	0.95

maximum as 2000−2003, and descending phase thereafter. It is interesting to note that all three datasets show a double maximum at the maximum phase of the solar cycle and an extended minimum between 2007−2010.

We also correlate the mean frequency shifts with the STARA total sunspot area and their mean magnetic field strength. In Fig. 2, we show the frequency shifts as a function of total sunspot area for USAF/NOAA[3] in the top panel and STARA (bottom panel) for the ascending, maximum and descending phases of the solar cycle. The linear Pearson correlation coefficient for the USAF/NOAA and STARA total sunspot area are 0.94 and 0.98, respectively. Both these quantities show a hysteresis-type behaviour for the different phases of the solar cycle, although the increase in solar oscillation frequencies precedes the increase in

[3] The United States Air Force/National Oceanic and Atmospheric Administration (USAF/NOAA) sunspot area data are compiled by David Hathaway and are taken from http://solarscience.msfc.nasa.gov/greenwch.shtml

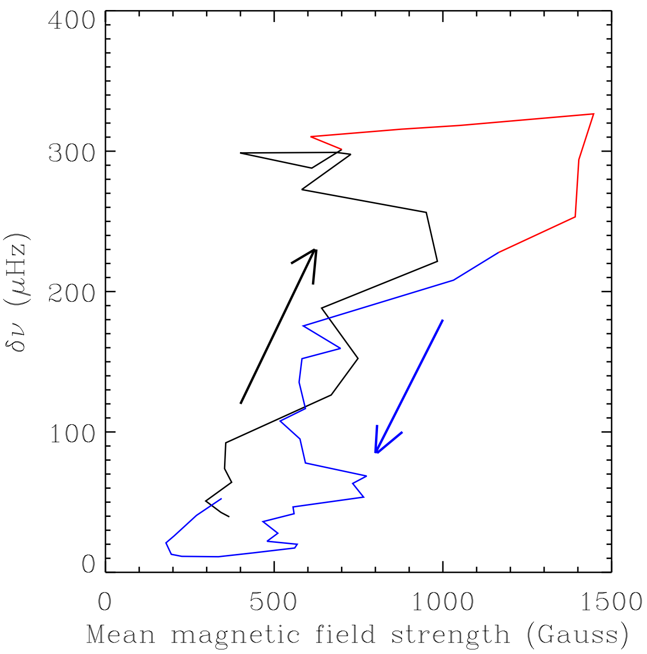

Fig. 3. Averaged p-mode frequency shifts, $\delta\nu$, plotted as a function of the mean magnetic field strength calculated from STARA. The black, red, and blue colours indicate the ascending, maximum, and descending phases of solar cycle 23, respectively. The arrows indicate the direction of time.

total sunspot area slightly. This finding is similar to Jain et al. (2009, see also Jimenez et al. 1998, for low-l degree modes), where they also obtained the time delay response, using other solar activity indices.

In Fig. 3 we show the frequency shifts as a function of the absolute value of the STARA-sunspots' mean magnetic field strength for the ascending, maximum, and descending phases of the solar cycle. Unlike with sunspot area, the variation in mean frequency shift shows a slightly unusual behaviour with this parameter. There is a crossing between the ascending and descending phases. The linear correlation coefficient for the STARA mean magnetic field strength is 0.83.

2. Discussion

We find that the maximum frequency shift coincides in time with the maximum sunspot numbers with a double peak. The frequency shifts on smaller time-scales often show a similar shape to the full solar-cycle shift. Is the frequency shift behaviour seen in Fig. 1 an indication of a *self-similar* Sun?

We also find that the frequency shifts show a hysteresis type behaviour with sunspot area (Fig. 2) and with mean magnetic field strengths (Fig. 3). Clearly, the difference in the shape of the hysteresis loop in the top and bottom panels of Fig. 2 suggests that the hysteresis does partially depend on the measurements, but the return-point memory for both measurements is remarkable. The difference in the two panels could be a result of the threshold applied to the STARA sunspot area calculations. In the STARA algorithm, sunspots with an area less than approximately 50 (in units of millionth of the solar hemisphere) are neglected, whereas the USAF/NOAA sunspot area calculations include areas of all the measured sunspots. It may also be noted that the sunspot areas as compiled by David Hathaway increases the USAF/NOAA spot areas by a factor of 1.4 after 1976. It should be noted, though, that the hysteresis does show a crossing for the mean magnetic field strength (see Fig. 3), suggesting that the partial ordering that was seen in Fig. 2 is not preserved for this parameter. A similar investigation but using a different method to measure sunspots' mean magnetic field strengths, may shed light on this issue. In any case, it is unlikely that the hysteresis between frequency shifts, and both the solar cycle indices (sunspot area and mean magnetic field strength) are totally unphysical.

The phenomenon of hysteresis is usually an indicator of multistability in a dynamical system (see for example, Mayergoyz 2012). It is, therefore, tempting to suggest that the solar cycle evolution of p-mode frequencies is a nonlinear phenomenon that has at least two existing stable states and that there is a phase difference between the time evolution of the p-modes and various sunspot parameters, such as sunspot area and the mean magnetic field strength. However, as also pointed out by Moreno-Insertis & Solanki (2000), some caution is necessary when p-mode frquency shifts are compared simply with a global solar-activity index, such as sunspot number, sunspot area, or their magnetic field strength, because these indices alone do not represent the full distribution of magnetic flux in the Sun, whereas p-modes sample magnetic fields throughout the Sun and the magnetic fields do affect the properties of the atmosphere, and therefore the oscillation frequencies and their resulting frequency shifts (see Evans & Roberts 1992; Jain & Roberts 1993; see also, Goldreich et al. 1991).

The p-modes are stochastically excited. As seen in the present study they seem to vary with solar cycle activity index such as the sunspot number. Therefore, the main question is whether the p-mode frequencies change only because of an increase in the perturbation resulting from an increase in the number of magnetic features, such as sunspots or plages or the properties of turbulence in the convection zone, which excites p-modes vary with solar cycle. Turbulence in the convection zone is likely to change the density and temperature of *local* background atmosphere, which may modify the frequencies. It is conceivable that changes to turbulence modify the frequencies of p-modes if the solar oscillations interact with turbulence in a nonlinear manner. However, the convection within the magnetically active regions is quite different and not well understood. Thus, it is not clear how the p-mode frequencies are directly affected *globally* by turbulence during the solar cycle. On the other-hand, it is conceivable that the turbulence modifies the near-surface frequency effects of uncertain origin but then why do these changes in the turbulent properties affect some frequencies of p-modes more than others and what happens to the turbulent convection zone during the extended solar minimum? A similar correlation study with a parameter intrinsic to the turbulent-dynamo theory (that relates to the p-mode frequencies) would be useful.

In this paper we have mainly been concerned with the correlation of frequency shifts with sunspot number provided by the international sunspot number, $R_{\rm I}$ and its comparison with the sunspot number calculated from STARA. Hysteresis phenomena have also been found with other solar indices such as 10.7 cm flux, Ca II K, He I, Mg II K, EUV, L_{α} lines, and International Sunspot Number (see Bachmann & White 1994) for solar cycles 21 and 22 (see also Jiménéz-Reyes et al. 1998; Suyal et al. 2012). Örzüc & Atac (2001) also showed similar phenomena between solar flare index and solar cycle indices, such as the sunspot area and the mean magnetic field strength for activity cycles 21 and 22. It is thus possible that the hystereses found in the present study for p-mode frequencies of solar cycle 23 suggest that many of the solar-activity indices follow different trajectories for the ascending and descending phases of the solar cycle, indicative of delays in the onset and decline of solar activity, with saturation at the extreme ends of the phases. A detailed dynamical analysis may be necessary with calculations of dynamical measures, such as Lyapunov exponents or permutation entropy for a simulated, as well as actual p-mode frequency dataset.

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