Angular-degree dependence of $p$-mode frequencies during solar cycle 23

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Abstract. We analyze simultaneous helioseismic observations collected by the ground- and space-based instruments during solar cycle 23 by computing oscillation frequencies for low- and intermediate-degree $p$-modes on a time scale of 36 days. We find that the frequency shifts corresponding to different angular degree, $\ell$, indicate different epochs for the onset of the solar cycle 24. The analysis also indicates the presence of double minima between cycles 23 and 24 for some range of $\ell$ values.

1. Introduction

The frequencies of solar oscillations vary with the solar activity cycle and the variations are used to infer the solar-cycle related changes inside the Sun. The extended minimum between cycles 23 and 24 has proved to be rather unusual. For the first time, the global mode frequency measurements showed an anti-correlation with the activity proxies during the extended minimum [1]. Further, oscillation modes with low angular degrees, particularly $\ell = 0$ and $\ell = 2$, suggest the onset of the cycle 24 occurred in the last quarter of 2007 [1, 2] while $\ell = 1$ modes from Global Oscillations at Low frequency (GOLF) and Birmingham Solar Oscillations Network (BISON), and intermediate degree modes from Global Oscillation Network Group (GONG) and Michelson Doppler Imager (MDI) onboard Solar and Heliospheric Observatory (SOHO), show the onset to be in early 2009 [3]. Therefore, it appears that the onset of the new cycle varies with the mode degree.

Here we present an updated analysis of the GOLF and GONG observations by computing oscillation frequencies with a cadence of 36 days with a 18-day overlap. The GOLF power spectrum, starting on 1996 May 1 and ending on 2010 January 1, is fitted with a Lorentzian profile. The series with a filling factor less than 70% were not used in this analysis resulting in a total of 269 time series for the GOLF data. The details of the fitting procedure can be found in [5]. The GONG data covers the period from 1996 May 1 to 2009 October 31 and consists of 273 overlapping data sets. The intermediate degree GONG frequencies were calculated using the standard GONG pipeline where the individual resonant peaks in the multi-tapered power spectrum are fitted with a Lorentzian profile [4]. For comparison and validating, we also use
Figure 1. Temporal evolution of the frequency shifts (symbols) calculated from GONG (left panel) and GOLF (right panel) 36-day time series. The red/thin line in each panel represents the International sunspot number, $R_I$. The black/thick line in the right panel depicts the smoothed frequency shifts obtained from the boxcar average over 21 points. The vertical line on the right panel indicates the error bar associated with the GOLF frequency measurements.

The temporal variations of the $p$-mode frequencies, i.e. the frequency shifts ($\delta \nu$), were calculated by comparing each fitted frequency with a reference frequency in the frequency range of $\nu = 2000$ and 3300 $\mu$Hz.

2. Results

2.1. Variation over solar cycle

The temporal evolution of the frequency shifts over the complete solar cycle 23 for both GONG and GOLF is shown in Figure 1. The GONG shifts are calculated from the common modes between $\ell = 0$ and 100 and comprise about 160 modes that are present in all time samples. The symbols when joined by a line (to guide the eye) clearly demonstrate the variation with the solar activity cycle shown by the red/thin line representing the International sunspot number, $R_I$. In comparison, the GOLF shifts which are calculated from $\ell = 0 - 2$ modes appear to be noisier due to averaging over a fewer modes as compared to the GONG. However, the solar cycle pattern is clearly visible when the points are smoothed by taking a boxcar average over 21 points (black/thick line).

3. Extended Minimum Phase

3.1. Sun-as-a-star observation

In order to investigate the extended solar minimum phase, we present the frequency shifts between 2007 and 2010 corresponding to individual low degree modes in Figure 2. Modes of different degree suggest different onsets of the cycle 24. However, as discussed earlier, the frequency shifts appear to be noisy and within the error estimates, so we compute a boxcar average over 21 points (shown by thick solid line). This curve confirms the result of [1], where $\ell = 0$ and 2 modes show the onset to be late 2007 while $\ell = 1$ shows the onset to be second quarter of 2009, generally agreeing with the observations of the surface activity indicators. Similar results are also inferred from the integrated GONG data (lower panels), $\ell$ of 0 and 2 shows the onset to be earlier than the $\ell = 1$ mode. As described in [1, 3], the zonal and sectoral modes are sensitive
Figure 2. Temporal evolution of the frequency shifts corresponding to (left) $\ell = 0$, (middle) $\ell = 1$, and (right) $\ell = 2$ modes obtained from GOLF (upper panels) and integrated GONG (lower panels) 36 day time series. The heavy solid line is the smoothed shifts obtained from a boxcar average over 21 points.

to the different latitudes, the modes that are sensitive to high latitudes of the Sun indicate an early onset of the cycle.

3.2. Resolved observations
We also analyze the frequency shifts as a function of the degree of the mode using the intermediate-degree mode frequencies calculated from the standard 36 day GONG time series. These shifts for different $\ell$ ranges are presented in Figure 3. Panels (a-b) suggest a minimum around early 2008, panel (c) shows the presence of double minima, one in late 2007 and the other around early 2009, while other panels show a minimum around early 2009.

4. Conclusions
We have analyzed integrated helioseismic observations collected by the space-based GOLF and ground based GONG instruments and investigated the angular degree dependence of the $p$-mode frequencies calculated on a time-scale of 36 days. We find that the temporal variations associated with the individual low degree modes are noisy while a running mean over 21 points equivalent to frequencies calculated from a period of 378 days confirm the findings of [1]; $\ell = 0$ and $\ell = 2$ mode frequencies show an upturn from the end of 2007 while the variation of $\ell = 1$ mode frequencies agree with those of the activity proxies. The frequencies obtained from the resolved GONG observations suggest that the onset of the new cycle is a function of the angular degree of the mode. We finally note that the presence of a 2-year periodicity in the Sun-as-a-star frequency shifts [7, 8] may affect the conclusions about the onset period of the new solar cycle.
Figure 3. Temporal evolution of the GONG frequency shifts for different $\ell$ ranges as marked on the top of each panel. The position of seismic minimum is different in different plots.

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