What Solar Oscillation Tell us About the Solar Minimum

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Abstract. The availability of continuous helioseismic data for two consecutive solar minima has provided a unique opportunity to study the changes in the solar interior that might have led to this unusual minimum. We present preliminary analysis of intermediate-degree mode frequencies in the 3 mHz band during the current period of minimal solar activity and show that the mode frequencies are significantly lower than those during the previous activity minimum. Our analysis do not show any signature of the beginning of cycle 24 till the end of 2008. In addition, the zonal and meridional flow patterns inferred from inverting frequencies also hint for a delayed onset of a new cycle. The estimates of travel time are higher than the previous minimum confirming a relatively weak solar activity during the current minimum.

1. Introduction

The delayed onset of solar cycle 24 and the prolonged period of minimal solar activity have invoked lots of interest in a variety of studies that might be useful to characterize the sun in a quiet state. Studies based on the helioseismic data have provided conflicting estimates of the length of previous cycle and shown that the present minimum is indeed the deepest in many aspects (Broomhall et al. 2009; Howe et al. 2009; Salabert et al 2009; Tripathy et al. 2009b). Since acoustic modes spend most of the time in the outer layers of the solar interior, the intermediate- and high-degree modes can be useful in interpreting the conditions in the convection zone. In this context, we investigate the response of these modes to the period of minimum activity and compare the response with the previous one.

2. Oscillation Frequencies and Solar Activity during Solar Minimum

The analysis presented here uses p-mode frequencies, ν, obtained from the Global Oscillation Network Group (GONG) in the 3 mHz band. It utilizes 21 36-day non-overlapping data sets in the frequency range $2800 \leq \nu \leq 3200$ μHz and degree range $20 \leq \ell \leq 100$ during minimum phase between solar cycles 23 and 24 from 2006 December 23 to 2009 January 16. We also use 21 data sets during the minimum between cycles 22 and 23 spanning over the period from 1995 June 12 to 1997 July 6.

The temporal variation of m-averaged frequency shifts ($\delta\nu$) with various measures of solar activity is shown in Figure 1. It should be noted that these m-
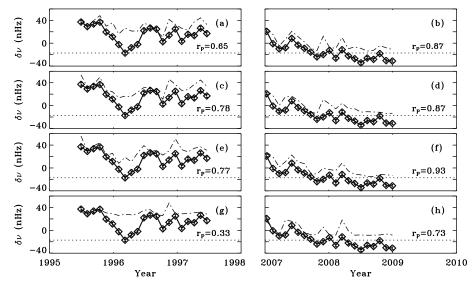
Figure 1.   Temporal evolution of the m-averaged frequency shifts (symbols) with scaled activity proxies (dashed-dot) during minima between cycles 22 and 23 (left), and 23 and 24 (right). The activity proxies used here are; (a-b) the international sunspot number, (c-d) the $F_{10.7}$ cm radio flux, (e-f) the Mt. Wilson plage strength index, and (g-h) the Mt. Wilson sunspot index. Pearson's correlation coefficients (r_P) between frequency shifts and solar activity are indicated in each panel. Dotted line represents the lowest frequency shift during the minimum between cycles 22 and 23.

averaged frequencies for global modes are averaged over all latitudes and can not be used to study the latitudinal distribution. The $\delta\nu$ for all 105 common modes are calculated with respect to the reference frequency which is determined by taking an average of the frequencies of a particular multiplet (n, ℓ). Although the frequency shifts follow the general trend of the solar activity in all cases, we find significantly different Pearson's correlation coefficients for all four activity indices (see Figure 1). These indices represent the changes in magnetic structures at different layers in the solar atmosphere. In a detailed study for the complete solar cycle, Jain, Tripathy & Hill (2009) have shown that the correlation between frequency shifts and activity proxies also differs when the cycle is divided into different phases.

It is evident from Figure 1 that the frequencies are lower and the correlation coefficients are higher for all activity proxies during the current minimum as compared to the previous minimum. The best correlation is found for the proxy depicting the change in weak component of the magnetic field, represented here by the strength of plages (Figure 1 e-f). The other indices (sunspot number, radio flux and the strength of sunspots) have major contribution from the strong component. The weakest correlation is found for the field strength of sunspots which is only influenced by strong fields. These findings are in agreement with an earlier study of local modes where inclusion of the weak component of the magnetic field was found to be necessary to explain the frequency shifts during the minimal-activity phase of the solar cycle (Tripathy, Jain & Hill 2009a).
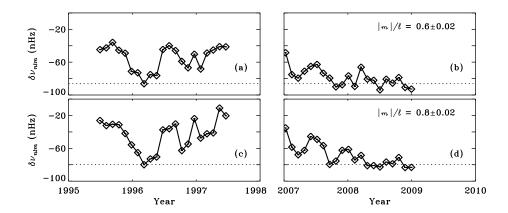
Figure 2.   The mean variation in frequency shifts at (a-b) $|m|/\ell \approx 0.6$ and (c-d) $|m|/\ell \approx 0.8$ during minima between cycles 22 and 23 (left), and 23 and 24 (right). The minimum shift at previous solar minimum is shown by the dotted line.

Although frequency shifts are known to vary in phase with the solar activity, we find an unusual trend during the current minimum. Solar activity shows an upward trend in the last quarter of 2008 while the shifts continue to decrease for the period considered in this analysis (for example Figure 1d) This anti-correlation was not seen in the minimum between cycles 22 and 23. Salabert et al (2009) have interpreted the anti-correlation between low-degree frequency shifts from GOLF, and 10.7 cm radio flux as a signature of the onset of the new solar cycle. However, their analysis suggests the onset of cycle 24 at the end of 2007 which is not supported by our analysis of intermediate-degree modes.

Since the magnetic activity related to a new solar cycle emerges first at mid-latitudes, it is possible to follow the changes in oscillation modes as a function of the latitude using different values of $|m|/\ell$. For $|m|/\ell=1$, the modes are sensitive to the regions near equator while $|m|/\ell=0$ represents modes at higher-latitudes. Figure 2 shows the mean variation in frequency shifts, $\delta\nu_{nlm}$, at selected values of $|m|/\ell$ representing the changes at mid/active-latitudes. As seen earlier, the frequencies are lower during current minimum and continue to decrease with time. The lowest value in the left panels coincides with the minimum between cycles 22 and 23 providing a reasonable estimate of the solar minimum. Although we do not see an increase in frequencies yet, the shifts for last two data points in Figures 2b and 2d are comparable. It might be an indication that the activity minimum has been reached in late 2008, however, the addition of more data sets is crucial to unveil the clear picture of the onset of solar cycle 24. It is worth mentioning that the minimum seen in intermediate-degree mode frequencies will be much later than the late 2007 as reported by Salabert et al (2009).

3.   Helioseismic Inferences and Comparison with Previous Minimum

The oscillation frequencies can be further used to infer characteristics of the solar interior. The migrating zonal flow pattern, known as the torsional oscillation,

is obtained by inverting the global mode frequencies (Howe et al. 2009). The analysis shows that the flow band associated with the new cycle has been found moving more slowly toward the equator than that observed during the previous minimum and suggests the length of solar cycle 23 to be approximately 12 years.

By using local helioseismology techniques, we can also study the meridional circulation in the solar interior. This extended solar minimum has given us the unprecedented opportunity to study the evolution of subsurface meridional flows without contamination from surface magnetic activity. A preliminary analysis of continuous GONG data using the ring-diagram technique suggests the formation of meridional flow "bumps" under the solar surface at high latitudes before the surface activity appears. Detailed results will be presented in an upcoming paper (González Hernández et al. 2009).

The analysis based on the technique of time-distance shows that the travel time of acoustic waves varies during the solar cycle and it decreases due to the presence of active regions. It is seen that there are no significant changes at high latitudes, while travel times at low latitudes are decreased by about 2 seconds during the maximum activity phase. The travel times during 2006-2008 are estimated to be 1-2 seconds higher than the previous cycle. These estimates also confirms that solar activity is relatively weak during the current minimum.

In summary, we find that the onset of solar cycle 24 is delayed and we do not see signs of the beginning of new cycle till the end of 2008.

References

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