Solar oscillations in cycle 24 ascending

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Abstract. Solar oscillation frequencies are known to follow the trend of solar cycle and show a strong correlation with various activity indices. However, the extended minimum between cycles 23 and 24 has raised several questions on the correlation between frequencies and solar activity where frequencies with different mode sets sensed different minima. In this paper, we analyze intermediate-degree mode frequencies as the Sun emerges from the unusually long period of minimal magnetic activity to study their behaviour with activity indices and compare results with the corresponding phase of cycle 23. We show that a model based on the rising phase of cycle 23 is a good predictor for behaviour in the rising phase of cycle 24.

1. Introduction
A precise knowledge of the solar interior and its variation with time is important to understand the origin of solar activity. The most simple and reliable way to infer variability of the interior is by examining its resonant modes. It is now well established that mode frequencies closely follow the trend of solar cycle and exhibit strong correlation with various proxies of solar activity [e.g. 1,2]. However, using uniform data for cycle 23, it has been shown that the degree of correlation depends on phase of the solar cycle [3]. While ascending and descending phases are tightly correlated with the surface activity, the maximum and minimum phases have relatively poor correlation. In addition, the analysis of frequencies during the recent extended minimum has demonstrated that different mode sets may exhibit different scenario; the most interesting finding is the disagreement in minima as sensed by low- and intermediate-degree modes [4,5]. In this paper, we analyze intermediate-degree mode frequencies for the ascending phase of cycle 24 to study how well these frequencies follow the solar activity after a long spell of extremely low activity.

2. Data
The $p$-mode frequencies used here are taken from three sources: the Global Oscillation Network Group (GONG) covering a period of 17 years from 7 May 1995 to 24 May 2012; the Michelson Doppler Imager (MDI) onboard Solar Heliospheric Observatory (SoHO) covering 15 years of data from 1 May 1996 to 24 Apr 2011; and the Helioseismic Magnetic Imager (HMI) onboard Solar Dynamics Observatory (SDO) covering a period of more than 2 years from 30 Apr 2010 to 9 Sep 2012. We have used MDI frequencies processed through the HMI pipeline [6]. While the GONG frequencies are calculated using overlapping 108-day timeseries spaced by 36 days, the MDI and HMI frequencies are for non-overlapping 72-day timeseries. In total, we use 171, 74 and 12 data sets from GONG, MDI and HMI, respectively with simultaneous observations.
Figure 1. Comparison of common $p$ modes observed in (a) GONG, (b) MDI and (c) HMI datasets. The bottom row shows $p$ modes common between (d) MDI and HMI datasets, and (e) all three datasets. The number of modes fitted in all GONG data are significantly smaller than those in the MDI and HMI data.

Figure 2. Variation of oscillation frequencies for two modes observed in all three data sets at (a) low frequency and (b) high frequency. The uncertainties in frequencies are smaller than the size of symbols. Shaded areas on left and right sides in these plots represent solar cycles 22 and 24, respectively.

from all three instruments for a year from 30 April 2010 to 25 April 2011. In order to study variation of frequencies with time, we analyze modes that are common in all data sets and are shown in Figure 1. It is seen that there is a significant difference in fitted modes using data from different instruments. We interpret the different mode sets to arise due to the difference in lengths of time series and data reduction techniques.

3. Results

In Figure 2 we show two examples representing the low- and intermediate-frequency modes as a function of time for all three data sets. The GONG frequencies are found to be lower than the MDI and HMI frequencies. However, as MDI and HMI frequencies are calculated using identical fitting method and 72-day timeseries, the frequencies of these two data sets are in better agreement.

To study temporal variation in oscillation frequencies, we calculate average frequency shift, $\delta \nu$, from the relation

$$\delta \nu(t) = \sum_{n,\ell} \frac{Q_{n,\ell}}{\sigma_{n,\ell}^2} \frac{\delta \nu_{n,\ell}(t)}{\sum_{n,\ell} Q_{n,\ell}} / \sum_{n,\ell} \sigma_{n,\ell}^2,$$

where $\delta \nu_{n,\ell}(t)$ is the change in the measured frequency with respect to a reference frequency, $\sigma_{n,\ell}$ is the uncertainty in the frequency measurement for a given $n, \ell$ multiplet and $Q_{n,\ell}$ is the inertia ratio. The reference frequency is calculated using a temporal mean over all the available data sets. In this analysis, we have used two sets of reference frequencies; the first set is calculated using modes shown in Figure 1(d) and second set is for Figure 1(e). The resultant frequency
shifts in the frequency range of $1.5 \, \text{mHz} \leq \nu \leq 4.0 \, \text{mHz}$ for $p$ modes are plotted in Figure 3. It is clearly seen that the frequencies vary in phase with the solar activity as discussed in earlier studies, however there is a significant variation in its magnitude depending on the modes used in the analysis. It is evident from Figure 3 that the MDI and HMI frequency shifts are consistently higher than the GONG but the overall shifts from low- to high-activity periods in all cases are approximately similar. In addition, the MDI and HMI shifts are in close agreement in the period of simultaneous observations.

To compare relative variation in frequencies with the change in solar activity $\delta i$ during ascending phases of cycles 23 and 24, we assume a linear relationship of the form $\delta \nu = a \, \delta i + b$, where coefficients $a$ and $b$ are obtained by performing a linear least square. Examples of the linear regression of GONG frequencies in the ascending phase of solar cycle 23 with 10.7 cm radio flux and sunspot numbers are shown in Figure 4(a-b). The solid line is the best regression

![Figure 3](image_url)

**Figure 3.** Temporal variation of frequency shifts calculated using (a) common modes in all MDI (green solid) and HMI (red dashed) datasets, and (b) common modes in all MDI (green solid), HMI (red dashed) and GONG (blue dotted) datasets. The yellow dashed-dot-dot-dot line in figure (a) represents the variation of the 10.7 cm radio flux. Shaded areas have the same meaning as in Figure 2.

![Figure 4](image_url)

**Figure 4.** (Left) Linear regression of the GONG frequency shifts and the change in activity proxies (a) 10.7 cm radio flux ($\delta F_{10}$) and (b) the international sunspot number ($\delta SSN$) for the ascending phase of solar cycle 23. The solid line represents the least-square fit. Models for cycle 23 are used to predict frequency variation in cycle 24. (Right) Temporal variation of modeled (black diamond) and observed frequency shifts in cycle 24 (blue circle) using (c) 10.7 cm radio flux and (d) international sunspot numbers.
Temporal variation of modeled (black diamond) and observed frequency shifts in cycle 24 for MDI (green circle) and HMI data (red triangle); The models are developed using MDI frequencies for the ascending phase of cycle 23 with (a) 10.7 cm radio flux and (b) international sunspot numbers.

Figure 5. Temporal variation of modeled (black diamond) and observed frequency shifts in cycle 24 for MDI (green circle) and HMI data (red triangle); The models are developed using MDI frequencies for the ascending phase of cycle 23 with (a) 10.7 cm radio flux and (b) international sunspot numbers.

fit and confirms that the data sets are consistent with the assumption of a linear relationship. This assumption is further tested by calculating Pearson’s correlation coefficients which are found to be $>0.98$ in both cases. These regression coefficients are further used to model mean shifts in the ascending phase of cycle 24.

Figures 4(c-d) and 5(a-b) compare observed and modeled variation of frequency shifts for ascending phase of cycle 24. We find a good correlation, i.e. $>0.96$ between the observed and modeled shifts, thus the change in frequency per unit solar activity obtained for the ascending phase of cycle 23 is a good estimate for frequency shifts in the same phase of cycle 24. In addition, we find a relatively higher correlation between observed and modeled frequencies when we use $F_{10}$ as an input to the regression model. This is in agreement with earlier results where frequency shifts are found to be better correlated with $F_{10}$ than SSN [3]. These findings indicate that the sensitivity of oscillation frequencies to the change of magnetic activity does not vary significantly for the same phase of solar cycles.

In summary, the continuous and improved measurements of oscillation frequencies for more than a solar cycle provide a deeper insight on the variability of solar interior. The obtained high linear correlation between frequency shifts and solar activity in the rising phase of cycle 24 is consistent with the previous findings. However, longer data sets covering the maximum phase are needed to provide better understanding on the role of magnetic field in the variation of oscillation frequencies.

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References

[1] Tripathy S C, Hill F, Jain K and Leibacher J W 2007 Solar Phys. 243 105-120
[2] Chaplin W J, Elsworth Y, Isaak G R, Miller B A and New R 2004 MNRAS 352 1102-1108
[3] Jain K, Tripathy S C and Hill F 2009 Astrophys. J. 695 1567-1676
[4] Jain K, Tripathy S C and Hill F 2011 Astrophys. J. 739 6
[5] Salabert D, García R A, Pallé P L, Jiménez-Reyes S J 2009 A&A 504 L1-L4
[6] Larson T and Schou J 2011 J. Phys. Conf. Ser. 271 012062