Variation of high-degree mode frequencies during the declining phase of solar cycle 23

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Abstract. We investigate the spatial and temporal variation of the high-degree mode frequencies during the declining phase of the solar cycle 23 and the extended minimum between the cycle 23 and 24. We find that the frequency shifts of high-degree modes obtained through the ring-diagram analysis in different phases of the solar cycle are not equally correlated with the local magnetic activity index.

1. Introduction
The acoustic frequencies of the Sun vary with the solar cycle and, in general, can be used as a tracer of magnetic activity [1]. However, recent studies using intermediate-degree global mode frequencies, both from GONG [2] and MDI [3], have shown complex variations during different phases of the solar cycle [4]. A similar study involving high-degree mode frequencies indicated that the correlation between frequency shifts and surface magnetic activity measured locally are significantly different during the two phases of the solar cycle [5]. Analyses of global frequencies during the extended minimum phase also indicate anti-correlation with the measurement of solar activity indices [6, 7]. In this context, we investigate the spatial and temporal variation of the high-degree mode frequencies during the declining phase of solar cycle 23 and the extended minimum phase between cycles 23 and 24.

2. Results
We use the ring-diagram technique [8, 9] to calculate the high-degree ($200 \leq \ell \leq 1100; 0 \leq n \leq 6$) mode frequencies during nine-equally spaced Carrington Rotations (CRs) covering the period from 2002 to 2009 (CR1985 to CR2081). The high-degree mode frequencies are determined for each ring-day (1664 minutes) over 189 regions on the solar disk covering up to 60 degrees in latitude from the disk center. For each wavenumber and radial order, the frequency shifts are computed relative to the spatial average obtained from the 189 tiles; these shifts are then averaged over all multiplets to yield an average frequency shift, $\delta \nu$. We also estimate the magnetic activity associated with each tile by calculating a local magnetic activity index (MAI) that represents the average over all of the pixels in a given magnetogram tile. Here, we use the 96-min MDI magnetograms mapped and tracked in the same way as the Dopplergrams, so these MAIs represent contributions from about 18 images.
A sequence of images showing the frequency shifts (top panels) and Magnetic Activity Index (bottom panels) corresponding to 189 dense pack tiles for four ring-days (1–4 November, 2003) during the high activity period of CR 2009. The shifts represent average values over all modes present in a given tile.

Same as Figure 1 but for low activity period of CR 2069 (24–28 April, 2008).

2.1. Spatial Variation

A sequence of images of the average frequency shift (top panel) and coeval magnetic activity index (bottom panel) for high- and low-activity periods corresponding to 1–4 November, 2003 and 24–28 April, 2008 are shown in Figure 1 and Figure 2, respectively. For each of the images, each pixel corresponds to a single tile in the 189 dense-pack mosaics. Once again the images confirm that during the high-activity phase the local frequency shifts act as a tracer of magnetic activity while during the low-activity period, the agreement is weaker.

For a quantitative analysis, we perform a straight-line least-squares fit between the average
frequency shifts and the MAI and also evaluated the linear Pearson’s correlation coefficient, \( r_p \), for each ring day. These are shown in Figure 3 as a function of MAI for all the CRs. We find that for MAI above approximately 6–7 G, the correlation is larger than 80% and then shows a steep decrease as the MAI decreases. We also note negative coefficients for CR 2057–2081 which corresponds to the extended minimum phase between the cycle 23 and 24 implying that the frequencies do not follow the strong magnetic field component all the time. It is also interesting to note negative slopes for low MAI values.

2.2. Temporal Variation

We have also investigated the temporal variation of the frequency shifts over each CR, where the frequency shifts of each multiplet is calculated by subtracting an average frequency over the entire CR for each of the disk position and then averaged over all the multiplets. An average MAI is also obtained by averaging the MAI of each location over the entire CR. Figure 4 shows the linear correlation coefficients between frequency shifts and MAI. It is evident that as the solar cycle progresses towards the minimum phase, the correlation steadily decreases. We also note a significant drop during the extended minimum period and a negative correlation when the solar activity was near the minimum phase. As discussed earlier, such a negative correlation is also seen in the case of global modes [6, 7].

3. Summary

The frequency shifts of high degree modes obtained through the ring-diagram analysis in different phases of the solar cycle illustrate that the shifts are not equally correlate with the local magnetic activity index. During the descending phase, the frequency shifts are strongly correlated, while during period of extended minimum phase both the spatial and temporal shifts are weakly correlated with MAI implying that the shifts can not be accounted by the regions of observed strong field component of the magnetic field alone. Thus we conjecture that the changes in acoustic high-degree mode frequencies may be associated with two components: strongly localized active regions and the quiet-sun magnetic field. The former explains the larger shifts while the later may be responsible for the smaller shifts in all phases of solar activity.
Figure 4. Linear correlation coefficients between frequency shifts and MAI for different CR’s.

Acknowledgments
This work utilizes data obtained by the Global Oscillation Network Group (GONG) program, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofísico de Canarias, and Cerro Tololo Interamerican Observatory. It also utilizes data from the Solar Oscillations Investigation/Michelson Doppler Imager on the Solar and Heliospheric Observatory. SOHO is a mission of international cooperation between ESA and NASA. This work was supported by NASA grant NNG 08EI54I.

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