Variation of Oscillation Mode Parameters over the Solar Cycle 23: An Analysis on Different Time Scales

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Abstract. We investigate the variation in the mode parameters obtained from time series of length 9, 36, 72 and 108 days to understand the changes occurring on different time-scales. The regression analysis between frequency shifts and activity proxies indicates that the correlation and slopes are correlated and both increase in going from time series of 9 to 108 days. We also observe that the energy of the mode is anti-correlated with solar activity while the rate at which the energy is supplied remains constant over the solar cycle.

1. Introduction

Observations show that the mode frequencies change with the solar cycle and the correlation between the frequencies and solar activity measured by different proxies is solar cycle phase dependent (see Jain, Tripathy, & Hill 2009, and references therein). There is also an indication that the correlation between frequency and activity depends on the length of the observation due to the finite lifetime of the modes (Tripathy et al. 2007). Therefore, it is important to understand the relation between mode frequencies and other mode parameters with solar activity on different time scales. With this objective, we have analyzed the Global Oscillation Network Group (GONG) time series data by splitting it into segments of length 9, 36, 72 and 108 days.

2. Data

The GONG data analyzed here cover the period between 7 May 1995 and 31 August 2007 and consist of 125 sets of time series of length 36 days. These are processed with a multi-taper spectral method to produce power spectra (Komm et al. 1999; Tripathy et al. 2007). The mode frequencies and other mode parameters are estimated by fitting the individual peaks (Anderson et al. 1990); not all modes are fitted successfully at every epoch due to the stochastic excitation nature of the modes. In this paper, we concentrate on the behavior of individual modes rather than the average quantities. Although each data set has a large number of multiplets, only 19 multiplets are found to be common to all of the data sets and have an inner turning point half-way between the tachocline and solar surface. These multiplets cover a frequency ($\nu$) range of 2138 – 3362 $\mu$Hz and degree ($\ell$) range between 50 and 81.

The mode parameters are correlated with four well known surface activity indicators: the integrated radio flux at 10.7 cm ($F_{10}$) obtained from Solar Geo-
Figure 1. (a) The temporal evolution of the frequency shifts corresponding to the multiplet \( n = 8, \ell = 72 \). The solid line shows the solar activity. (b) The shifts as a function of the radio flux for the same mode. The solid lines denote the linear fits between them. The vertical lines on the bottom indicate 1σ errors in the increasing order of the length of the time series. Different symbols indicate different lengths and are marked in (b).

physical Data (SGD), Magnetic Plage Strength Index (MPSI) from Mt. Wilson magnetograms (Ulrich 1991), the International Sunspot Number \((R_I)\) obtained from SGD and Mg II core-to-wing ratio (Viereck et al. 2001)

3. Results

Figure 1(a) shows the temporal evolution of frequency shifts corresponding to the \( n = 8, \ell = 72 \) multiplet with respect to the average frequency of the mode; different symbols correspond to time series of different lengths. A distinct temporal variation depicting the solar activity cycle is easily observed in each data set. Although the modes are well resolved in the 9-day time samples, a large scatter is seen for the frequencies, probably due to the lower frequency resolution and broader line widths. Figure 1(b) demonstrates the linear relationship between the frequency shifts and 10.7 cm radio flux measurements.

As an example of the relation between the frequency shifts and activity indices, the left panel of Figure 2 shows the correlation coefficients for four different multiplets as a function of the length of the time series. For all of the activity indices considered here, the correlation improves with the length but the nature of the increase is significantly different for different multiplets. For example the \( n = 8, \ell = 81 \) multiplet shows a steep increase in correlation from 9 to 108 days while for the \( n = 8, \ell = 63 \) multiplet, the correlation flattens after 36 days. The variations of the slope as a function of the correlation coefficients for different data sets are shown in the right panel of Figure 2. Each point in the figure represents a common multiplet. We find that the correlation and slopes are correlated and both increase from 9 days to 108 days. However, our earlier studies (Tripathy et al. 2007) involving average frequency shifts had shown that the slopes obtained from 9 days are higher than those from 108 days. Thus, the behavior of individual modes appear to be different from their average quantities.
Global Mode Parameters over Solar Cycle 23

Figure 2. The left panels show the correlation coefficients obtained from the linear fit between frequency shifts and different activity indices (marked in the bottom panel) for four different multiplets as a function of sample length. The right panel shows the slopes obtained from $F_{10}$ as a function of the correlation coefficient; each point denotes a common multiplet. The symbols represent different time segments and are indicated in the panel.

Figure 3. The temporal evolution of (a) mode energy and (b) energy supply rate for the $n = 8, \ell = 72$ multiplet. The symbols have the same meaning as in Figure 1.

We correct the mode amplitudes and line widths for gaps in the temporal window function and then combine them to estimate the mode energy ($\propto A \times \Gamma$) and energy supply rate ($\propto A \times \Gamma^2$) assuming stochastic excitation (Goldreich et al. 1994). The temporal evolution of these parameters for the $n = 8, \ell = 72$ multiplet is shown in Figure 3. As discussed in Komm et al. (2002), the plots demonstrate an annual modulation. We further observe that the energy of the mode (Fig. 3a) is anti-correlated with solar activity with correlation coefficients of $-0.62$, $-0.83$, $-0.86$, and $-0.90$ with $F_{10}$ for 9 to 108 days.
respectively. This again demonstrates that the correlation increases with the length of the time series. On the other hand, the energy supply rate (Fig. 3b) shows only short-term variations and no apparent correlation with the solar activity cycle. These general behaviors are consistent with those reported by Chaplin et al. (2000) for the low-degree modes. Further, we also note differences between energy and energy supply rate obtained from time series of different lengths; the values are higher for shorter time series. Similar to the mode frequency, it is also possible that different modes may behave differently and as a result the average behavior may be different than for individual multiplets.

4. Conclusion

Analyzing mode parameters of individual multiplets for data sets of different lengths, we find that the slope and linear correlation coefficients between mode frequencies and activity indicators increases with the length of the time series. In all cases, the slopes are found to be correlated with the correlation coefficients. We also observe that the mode energy decreases with increase in solar activity while the energy supply rate is approximately constant over the entire solar cycle; the values of these parameters are progressively higher for shorter time series. The study also indicated that the behavior of individual modes may be different from their average behavior. Additional work is in progress to confirm these findings.

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