GONG p-MODE FREQUENCY CHANGES WITH SOLAR ACTIVITY

A. BHATNAGAR, KIRAN JAIN, AND S. C. TRIPATHY

Udaipur Solar Observatory, Physical Research Laboratory, P.O. Box 198, Udaipur-313 001, India; arvind@uso.ernet.in, kiran@uso.ernet.in, sushant@uso.ernet.in

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ABSTRACT

We present a correlation analysis of GONG p-mode frequencies with nine solar activity indices for the period from 1995 August to 1997 August. This study includes spherical harmonic degrees in the range 2–150 and the frequency range of 1500–3500 μHz. Using three statistical tests, the measured mean frequency shifts show strong to good correlation with activity indices. A decrease of 0.06 μHz in frequency during the descending phase of solar cycle 22 and an increase of 0.04 μHz in the ascending phase of solar cycle 23 are observed. These results provide the first evidence for change in p-mode frequencies around the declining phase of cycle 22 and the beginning of new cycle 23. This analysis further confirms that the temporal behavior of the solar frequency shifts closely follow the phase of the solar activity cycle.

Subject heading: Sun: activity — Sun: oscillations

1. INTRODUCTION

Solar surface phenomena such as sunspots, the magnetic field, the 11 yr solar cycle, and associated activities are the consequence of dynamical processes occurring inside the Sun. The fundamental parameters responsible for most of the activities are the magnetic and velocity fields; thus the acoustic mode (p-mode) frequencies could be influenced by the solar activity. Hence, a relation between the solar frequencies and activity indices may throw some light on the changes occurring deep in the solar interior. The observed variation in frequencies is due to the changes in the internal temperature structure and are correlated with the variation in the surface temperature. Observations made during the rising phase of cycle 22 by the Big Bear Solar Observatory (BBSO) group found an increase of about 0.4 μHz in mean frequency during the period 1986–1989 (Libbrecht & Woodard 1990). Subsequently, Goldreich et al. (1991) theoretically showed that the variations in the solar p-mode eigenfrequencies are related to the perturbations in the magnetic flux at the Sun’s surface. These theoretical results were confirmed by Woodard et al. (1991), where the variation of frequencies on a timescale as short as 3 weeks with the absolute value of the magnetic field strength was shown. Now there is growing evidence that the mode frequencies vary with solar activity. Bachmann & Brown (1993), using the High-Altitude Observatory’s (HAO) Fourier Tachometer data for l between 20 and 60 in the frequency range of 2600–3200 μHz, showed that the p-mode frequency shifts correlate remarkably well with six solar activity indices during 1984 October through 1990 November. For the low-degree modes (l ≤ 3) and during different time epochs, several groups (Anguera Gubau et al. 1992; Régulo et al. 1994; Jiménez-Reyes et al. 1998) have shown that the frequency shifts are well correlated with the solar activity cycle.

It has also been shown that the frequency-splitting coefficients vary with solar cycle (Kuhn 1988; Woodard & Libbrecht 1993). It was pointed out that the even-order coefficients are sensitive to the solar cycle or to the latitude-dependent properties, while the odd-order coefficients reflect the advective, latitudinally symmetric part of the perturbations caused by rotation. Recently, using the Global Oscillation Network Group (GONG) data, Anderson, Howe, & Komm (1998) have found evidence for small shifts in the central frequencies and splitting coefficients. From the solar oscillation data obtained from the Michelson Doppler Imager on board the Solar and Heliospheric Observatory, during 1996 May 1 through 1997 April 25, Dziembowski et al. (1998) also detected a significant trend in the splitting coefficients.

Motivation for the present work arose as a result of the availability of high-precision frequencies from the GONG network, and for extending the earlier studies to include the declining phase of cycle 22 and the beginning of cycle 23. In this study, we also look for a possible correlation between the p-mode frequency shifts and the nine solar activity indices representing the photospheric, chromospheric, and coronal activities.

2. OSCILLATION DATA AND SOLAR ACTIVITY INDICES

The GONG data (Hill et al. 1996) used in this study consist of eight data sets covering a period of 2 year from 1995 August 23 to 1997 August 11, in the frequency range between 1500 and 3500 μHz and l from 2 to 150. This period covers the GONG months (GMs) 4–9 (1995 August 23–1996 March 25) of 36 days each, GMs 12–14 (1996 June 6–September 21), and GMs 21–23 (1997 April 26–August 11) of 108 days each. The period from 1995 August through 1996 September covers the declining phase of solar cycle 22, whereas the period from 1997 April to August refers to the beginning of cycle 23.

For calculating the frequency shifts, we have used the frequency of GMs 12–14 as a reference. The choice of this standard frequency has been made in view of two reasons: (1) that this datum lies in the middle of the period covered in this study and (2) that it represents the period of minimum solar activity. The mean frequency shift is found from the
following relation:

\[ \delta v(t) = \sum_{nl} \frac{Q_{nl}}{\sigma_{nl}} \delta w(t) \sum_{nl} \frac{Q_{nl}}{\sigma_{nl}}, \]

where \( Q_{nl} \) is the inertia ratio as defined by Christensen-Dalsgaard & Berthomieu (1991), \( \sigma_{nl} \) is the error in frequency measurement, as provided by GONG, and \( \delta w(t) \) is the change in the measured frequencies for a given \( l \) and radial order \( n \). We have neglected those node modes for which \( \sigma_{nl} > 0.1 \mu Hz \) in order to avoid large errors in calculating the mean shifts. The resulting mean weighted frequency shift \( \delta v \) is plotted against the GONG months for four different \( l \)-ranges (2 \( \leq l \leq 19 \), 20 \( \leq l \leq 60 \), 61 \( \leq l \leq 150 \), and 2 \( \leq l \leq 150 \)) and is shown in Figure 1. For the interval GMs 4–9, the frequency shift shows a systematic decrease of about 0.06 \( \mu Hz \) for all \( l \)-values, while for GM 9–23, the mean shift shows an increase of 0.04 \( \mu Hz \), indicating that the solar oscillation frequency varies with solar activity.

We have correlated the mean frequency shifts with the following different solar activity indices: the international sunspot number, \( R_s \), obtained from the Solar Geophysical Data (SGD); the Kitt Peak Magnetic Index (KPMI) from Kitt Peak full-disk magnetograms (Harvey 1984); the Stanford Mean Magnetic Field (SMMF) from SGD; the Magnetic Plage Strength Index (MPSI) from Mount Wilson magnetograms (Ulrich et al. 1991); the total flare index (FI) from SGD and T. Ataç (1999, private communication); He I, the equivalent width of He I \( \lambda 10830 \) averaged over the whole disk from Kitt Peak; Mg II, the core-to-wing ratio of the Mg II line at 2800 A from the Solar Ultraviolet Irradiance Monitor (SGD); \( F_{10} \), the integrated radio flux at 10.7 cm from SGD; and Fe xiv, the coronal line intensity at 5303 A from SGD. A mean value was computed for each activity index over the interval corresponding to the same GONG month.

3. ANALYSIS AND RESULTS

To study the relative variation in frequency shift \( \delta v \) with activity index \( i \), we assume a linear relationship of the following form:

\[ \delta v = ai + b, \]

where \( \delta v \) includes the mean error in the measured frequencies. The slope, \( a \), and the intercept, \( b \), are obtained by performing a linear least-squares fit. Figure 2 shows a typical plot of our analysis for all modes between 2 and 150. The solid line represents the best-fit regression line and shows that the data are consistent with the assumption of a linear relationship. The bars represent 1 \( \sigma \) error in fitting. We also carried out a \( \chi^2 \) test, which takes into account the statistical uncertainties of each of the frequency shifts. Because there is no reliable estimate available of the uncertainties in the measurement of activity indices, those are not included in the fitting.

The linear relationship given in equation (2) is further tested by calculating the parametric Pearson’s coefficient, \( r_p \), and the nonparametric Spearman’s rank correlation coefficient, \( r_s \), along with their two-sided significance, \( P_p \) and \( P_s \), respectively, for all the \( l \)-ranges. As a typical example, these parameters are given in Table 1, for the \( l \)-range of 2–150. From the table, it is clear that a positive correlation exists for all the activity indices. We note that the best correlation is obtained for the Mg II index, while \( F_{10} \), Fe xiv indices show good correlation. The SMMF shows poor correlation, perhaps because of large gaps in the available data. Normally, we expect that better correlation should exist between the magnetic activity and \( \delta v \), since this is the fundamental parameter for all solar activity. However, from Table 1, we notice that the radiative indices (\( F_{10} \), Mg II, and Fe xiv) show better correlation as compared with magnetic field indices. Bachmann & Brown (1993) using the HAO data had obtained a similar result. The reason for such a difference in the level of correlation needs further investigation.

In order to investigate the degree dependence of frequency shifts with activity indices, we carried out a statistical analysis for three different ranges of \( l \). It is seen that the fitting parameters, \( a \) and \( b \), do not show significant variation with \( l \). The lowest \( \chi^2 \) values are found for 2 \( \leq l \leq 19 \), while for 20 \( \leq l \leq 60 \) and 61 \( \leq l \leq 150 \) the \( \chi^2 \) values are higher. It is further noted that the correlation

| Activity Index | Intercept \( b \) (\( \mu Hz \)) | \( \chi^2 \) | \( r_p \) | \( P_p \) | \( r_s \) | \( P_s \) |
|---------------|-------------------------------|-------------|----------|--------|--------|--------|
| \( R_s \)      | 0.002 ± 0.0001  \( \mu Hz \)  | −0.034 ± 0.001  | 344 0.82 | 0.023  | 0.93 | 0.002 |
| KPMI          | 0.029 ± 0.001  \( \mu Hz G^{-1} \) | −0.221 ± 0.008  | 461 0.81 | 0.025  | 0.71 | 0.071 |
| \( F_{10} \)  | 0.005 ± 0.002  \( \mu Hz s^{-1} \) | −0.345 ± 0.011  | 144 0.93 | 0.002  | 0.93 | 0.002 |
| He I          | 0.010 ± 0.0004  \( \mu Hz m^{-1} \) | −0.449 ± 0.017  | 480 0.76 | 0.049  | 0.61 | 0.148 |
| SMMF         | 0.0004 ± 0.0002  \( \mu Hz \mu T^{-1} \) | −0.009 ± 0.002  | 1130 0.16 | 0.729  | 0.21 | 0.645 |
| MPSI          | 0.191 ± 0.006  \( \mu Hz G^{-1} \) | −0.031 ± 0.0009  | 266 0.87 | 0.011  | 0.93 | 0.002 |
| FI            | 0.023 ± 0.0008  \( \mu Hz \) | −0.017 ± 0.0005  | 373 0.83 | 0.020  | 0.93 | 0.002 |
| Fe xiv        | 0.012 ± 0.0004  | −0.048 ± 0.001  | 128 0.93 | 0.006  | 0.94 | 0.005 |
| Mg II         | 38.210 ± 1.172  \( \mu Hz \) | −9.712 ± 0.297  | 68 0.97 | 0.003  | 0.90 | 0.005 |

\* In units of \( \mu Hz \) sr/10^{16} \ W.
coefficients, \( r_p \) and \( r_s \) for all \( l \)-ranges, have values between 0.75 and 1.0 for all solar indices except for He I and the SMMF. Comparing \( r_p \) and \( r_s \) values for all activity indices, it is noted that for \( 2 \leq l \leq 19 \), these values are systematically less, indicating a week correlation as compared with the other \( l \)-ranges. Thus there appears to be some evidence that the frequency shift depends on \( l \).

Comparing our results for \( 20 \leq l \leq 60 \) with those of Woodard et al. (1991) and Bachmann & Brown (1993) for modes of similar degrees (Table 2), we find that the magnitude of slope \( a \) is comparable in all the three cases for the KPMI index, the only index common in all three analyses. However, a small difference of 0.003 \( \mu \text{Hz} \) between the GONG and BBSO data and 0.001 \( \mu \text{Hz} \) between the GONG and HAO data is noticed. This difference may be due to different frequency intervals and phases of the solar cycle. A detailed comparison between the BBSO and HAO results was made by Régulo et al. (1994). The other four indices considered in HAO and our work show similar correlation.

The temporal behavior of the solar frequency shifts and the mean monthly sunspot number \( R_s \) are shown in Figure 3. The diamonds represent the HAO data for the period 1984 October–1990 October, while the triangles indicate the GONG data for the period 1995 August–1997 August. A polynomial of order \( n \) of the form

\[
\delta v = a_0 + \sum_{i=1}^{n} a_i d^i
\]

is fitted separately to each set of frequency shift, \( \delta v \), since the reference frequencies for HAO and GONG data are different. Here \( a_0 \) and \( a_i \) are the fitting coefficients, and \( d \) is the

| ACTIVITY INDEX | GONG ANALYSIS | HAO ANALYSIS |
|---------------|---------------|--------------|
|               | \( a \)       | \( b \)       | \( \chi^2 \) | \( a \)       | \( b \)       | \( \chi^2 \) |
| KPMI          | 0.024         | -0.182       | 216         | 0.023       | -0.306       | 434          |
| \( F_{10} \)  | 0.004         | -0.307       | 60          | 0.003       | -0.345       | 153          |
| He I          | 0.009         | -0.410       | 170         | 0.011       | -0.667       | 184          |
| MPSI          | 0.171         | -0.031       | 94          | 0.136       | -0.168       | 166          |
| Mg II         | 33.986        | -8.643       | 22          | 20.96       | -5.700       | 134          |

* Units of \( a \) and \( b \) are the same as given in Table 1.

b For BBSO, \( a = 0.027 \mu \text{Hz G}^{-1} \).
number of days after 1981 January 1. The best fit for the HAO data is obtained with a polynomial of order 4, while a polynomial of order 2 fits the GONG data. The fitting coefficients for the HAO data are $a_0 = 0.557$, $a_1 = 1.583 \times 10^{-4}$, $a_2 = -1.107 \times 10^{-6}$, $a_3 = 5.839 \times 10^{-10}$, and $a_4 = -8.282 \times 10^{-14}$; for the GONG data these are $a_0 = 10.948$, $a_1 = -3.847 \times 10^{-3}$, and $a_2 = 3.369 \times 10^{-7}$. From this plot it is evident that the mean frequency shifts systematically follow solar activity cycle 22 and the beginning of cycle 23.

We conclude that a positive and linear correlation exists between the frequency shift and the nine solar activity indices. It is observed that the radiative indices show better correlation as compared with the magnetic indices. This analysis shows a decrease of 0.06 $\mu$Hz in weighted frequency during the declining phase of solar cycle 22 and an increase of 0.04 $\mu$Hz during the ascending phase of cycle 23. Our finding confirms that the temporal behavior of the solar frequency shifts closely follows the phase of the solar activity cycle, and we conjecture that the same trend will continue during cycle 23.

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