STUDIES OF THE SENSITIVITY OF P-MODE OSCILLATION FREQUENCIES TO CHANGING LEVELS OF SOLAR ACTIVITY

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ABSTRACT

Most studies of the solar cycle dependence of the p-mode oscillation frequencies have employed long-duration observing runs. Recently, Rhodes et al. (2002) have employed observing runs as short as three days in length using MDI data sets. The use of such short time series has resulted in a higher sensitivity (as measured in the slope of the linear regression of frequency differences upon the 10.7-cm flux differences) than did the use of long time series that averaged over regions varying widely in their levels of activity. Here we address the question of whether we can confirm this increased sensitivity by employing observing runs as short as three days in duration by using GONG+ data. We have employed GONG+ observations obtained during two different intervals in 2001 for these studies.

Key words: solar oscillations; frequency shifts.

1. INTRODUCTION

While it is now a well-established fact that the frequencies of the low- and intermediate-degree solar p-mode oscillations do indeed change with time in response to changing levels of solar activity, there is currently no consensus as to the solar origin of these changes. This situation was summarized clearly by Kuhn (2001), who described the various changes which have been seen in solar f- and p-mode frequencies, frequency splittings, horizontal flow velocities, and solar diameter measurements as diagnostics of what he called the "acoustic solar cycle".

2. GENERATION OF POWER SPECTRA FROM GONG+ VELOCITY IMAGES

The data sets for this analysis came from two separate runs in 2001: March 23 through March 26, and June 4 through June 13. During the March run, GONG+ was not fully established and full-disk velocity images were available only from the Big Bear site. During the 12-day run in June, observational data was available from the sites at Big Bear, Learmonth, and Cerro Tololo. When the data was retrieved through the GONG Data Storage and Distribution System (DSDS) over a year ago, velocity images from the remaining GONG+ sites were not yet available. These sets of data represent some of the very first high-resolution data collected by the GONG+ program. Figure 1 shows a plot of all the available data for 2001. The 5-day March run from Big Bear covers days 82 to 86 and the 12-day June run covers days 155 to 166.

The GONG+ images were processed utilizing code developed for analyzing images taken at the 60-Foot Solar Tower at the Mt. Wilson Observatory. Since the local data reduction software does not employ FITS images, the first processing step was the con-
version, for each minute, of the GONG+ FITS images into a 860x860 pixel, 16-bit integer array and a separate file containing the FITS keywords. These FITS headers were kept for inclusion of the keywords into subsequent processing steps.

The next step involved a multistage calibration procedure performed on the GONG+ full-disk velocity images. Each of the calibration steps was performed using specific keywords from the FITS headers. These calibration steps were performed separately and prior to the remaining reduction of the images. The first step was the conversion of the pixel values in the images into units of m/s. The second step accounted for the motion of each site with respect to the Sun, and the third step accounted for the velocity offset between sites. Once all of these calibration steps were performed, the component of the observer’s motion due to rotation was removed. The component of motion due to Earth’s revolution about the Sun was not taken into account.

Upon completion of the calibration procedure, the spherical harmonic decomposition step was performed using a modified version of the 60-Foot-Solar-Tower SHC-code. The SHC-code was modified to read the heliographic coordinates from the extracted FITS header and to apply these values to each individual velocity image. When we processed the March data we employed the same upper degree limit of 800 that we employ for our Mt. Wilson data. By the time we began processing the June data, we had modified our code to extend the maximum \( \ell \)-value to 1000. The time series of spherical harmonic coefficients from each observing day were transposed into one-dimensional time series for each \( (\ell, m) \) pair. The time series was extended with zeroes to a length of 32,768 minutes for each of the three-day sets. The one-dimensional power spectra were then computed from these time series in standard fashion.

3. GENERATION OF \( p \)-MODE DATASETS FOR TEMPORAL STUDIES

The \( p \)-mode frequency datasets which we employed in this study were computed with our WMLTP, “Windowed, Multiple-Peak, Averaged-Spectrum”, fitting method. As its name implies, the WMLTP method is applied to \( m \)-averaged power spectra. This method employs a sum of as many as nine such peaks and it convolves the resulting theoretical profile with the power spectrum of the temporal window function of each observing run. The details of the WMLTP method are given by Rhodes et al. (2001). This fitting method was applied to a total of six sets (2 in March and 4 in June) of \( m \)-averaged GONG+ power spectra which were computed from observing runs that were 4320 minutes in length. The WMLTP fitting method used the theoretically-predicted \( p \)-mode velocity eigenfunction component ratios along with a leakage matrix which had been generated using a small radius error and a small amount of optical distortion to generate a complete set of \( p \)-mode fitting parameters for degrees up through 800 from the March runs and up through 1000 from the June runs. Figure 2 shows a \( \ell-\nu \) diagram for one of these four 3-day June runs.

![Figure 2. \( \ell-\nu \) plot for one of the four, 3-day June 2001 GONG+ runs computed for the range June 10 through June 12.](image)

4. SOLAR CYCLE-DEPENDENT FREQUENCY SHIFTS

To extend previous studies of \( p \)-mode frequency shifts so that both the high-frequency and high-degree modes would be included in the comparisons, we inter-compared all of our various GONG+ datasets, yielding a total of fifteen tables of frequency shifts. In order to study the dependence of these frequency shifts upon changing levels of solar activity, we also computed the average 10.7-cm radio flux and the average magnetic plage strength index for each observing interval. In the top panel of Figure 3 we show the average 10.7-cm radio flux values as a function of time for all of our different frequency datasets computed to date. These include longer-duration observing runs available to us from MDI and MWO in addition to the GONG+ observing runs. The points on the plot span the same time as the frequency datasets in order to place the levels of solar activity in the context of the most recent 11 years. This figure indicates that we have been able to obtain frequency datasets covering more than one entire solar cycle. In the bottom panel of Figure 3 we show the daily 10.7-cm flux values for each of the 5 days in March 2001 and each of the 12 days in June 2001 which we have analyzed.

In Figure 4 we show the frequency dependence of the unbinned and binned frequency shifts between the first and third of our four June datasets. Since the 10.7-cm flux was higher during the third of our four 3-day runs in June than it was during the first of these four runs, most past studies of the temporal behavior of the \( p \)-mode frequencies would predict that those frequencies would have increased along with the rising level of activity between these two runs. Figure 4 shows that such frequency increases were seen, but only up to a frequency of about 5000 \( \mu \)Hz. On the other hand, for frequencies between 5000 and about 6200 \( \mu \)Hz the frequencies actually went down from the first interval to the second.

To better illustrate this anti-correlation in the behavior of the temporal frequency shifts in the lower and higher frequency regimes, we have plotted the
Figure 3. (top) Average 10.7-cm radio flux (corrected to 1 AU) for different frequency datasets versus time over the past 12 years. (bottom) Daily 10.7-cm flux values during each of the 17 GONG+ observing days.

Figure 4. Frequency dependence of unbinned and binned frequency differences between GONG+ (06/10-12/01) - GONG+ (06/04-06/01). a.(left), shows the frequency differences vs. frequency for all values up to 7000 µHz. b.(right), shows the frequency dependence of the average frequency differences in bins that were 250 µHz wide. Note, that the vertical scales are different in these two panels.

frequency dependence of the four sets of binned frequency differences which resulted when we compared the frequencies of the four June runs with those of the March 26-27 run, in Figure 5. These latter two days of the March runs corresponded to a period of high 10.7-cm flux, as indicated in Figure 3. In fact, the level of 10.7-cm flux during both of these two days was considerably higher than it was during any of the four 3-day runs in June. By subtracting the set of frequencies computed from the 3/26-27/01 run, from the sets of frequencies computed from each of the four June runs, we were able to compute four different sets of frequency differences, each set of which corresponded to a time interval of decreasing solar activity. For such intervals of decreasing solar activity we would have expected the frequency differences to be negative up to \( \nu = 5000 \) µHz and to become positive for higher frequencies. This was indeed the case, as can be seen here in Figure 5. Furthermore, since the 06/04/01 - 06/06/01 run had the lowest 10.7-cm flux of any of the June runs, while the March 26-27 run had the highest such flux, we would have expected that the frequency differences between these two runs would have produced the strongest dip at 5000 µHz, as illustrated by the dashed curve in Figure 5. On the other hand, the comparison of the two June datasets which we illustrated in Figure 4 corresponded to an increase in the level of solar activity between the two runs, and the entire curve in that figure can be seen to anti-correlate with all four of the curves in Figure 5.

In order to study the response of these GONG+ frequency shifts to changing levels of solar activity in more detail, we first selected four different points along the curves of Figure 5. Specifically, we selected the frequencies of 3625, 4875, 5625 and 5875 µHz as being representative of the low- and high-frequency regimes of our curves. Next we subtracted the 10.7-cm flux values of the different observing runs from one another and we generated a table of differences in the radio flux. Next, we performed linear regression analyses of the four sets of frequency shifts upon the differences in 10.7-cm flux. The results of regressing the binned shifts for the four frequencies at 3625, 4875, 5625 and 5875 µHz upon the differences in the 10.7-cm flux are shown in Figure 6. As with most past studies of the low- and intermediate-degree modes, the frequency shifts at 3625 and at 4875 µHz show positive slopes, with values of 8.65 and 25.21 nHz/SFU, respectively (where SFU=1 solar flux unit). Interestingly, these slopes are relatively shallow with respect to the slopes which resulted from the comparison of MDI 3-day runs, reported elsewhere during this meeting by Rhodes et al. (2003). These slopes are also more similar to those using long-duration runs where modes have died out or have been averaged over a long period of time. For the frequency shifts at 5625 and 5875 µHz the slopes are -17.92 and -44.58 nHz/SFU, respectively. These negative slopes indicate an anti-correlation with the 10.7-cm solar flux. In all four panels of Figure 6 the open-squares are representative of frequencies computed for \( \ell \) up to 800, while the filled-squares are representative of frequencies computed for \( \ell \) up to 1000.
Finally, to obtain even more sensitivity to the changes in solar activity, we subtracted the frequency shifts observed at $\nu = 5625$ $\mu$Hz from the frequency shifts observed at $\nu = 4875$ $\mu$Hz. These differences in the frequency shifts are plotted versus the differences in the 10.7-cm flux in Figure 7. Because both sets of frequency shifts are sensitive to changes in solar activity, but in an opposite sense, the difference in these two shifts is even more sensitive to changes in activity than is either frequency shift alone. The linear regression fit to all of the pairs of points has a slope of 43.13 nHz/SFU. This value is again, similar to results obtained from long-term runs. Rhodes et al. (2002) computed a slope of 58 nHz/SFU for the same $\Delta(\nu = 4875 - \nu = 5625)$ $\mu$Hz versus $\Delta$10.7-cm flux, for all of the MDI short-term and long-term runs combined. Since these latter two slopes are in rough agreement, we can say that the $p$-modes seen in the GONG+ spectra correlate with short-term changes in the level of solar activity with a slope similar to that found by comparing observing runs that were long in comparison with the 3-day runs employed in this study. The fact that our GONG+ slopes were all smaller than were the corresponding slopes reported by Rhodes et al. (2003) from their comparisons of MDI 3-day runs, indicates that our GONG+ comparisons did not confirm the expectations we had when we began our study of the GONG+ runs. We are now trying to understand these differences. Perhaps the differences are due to the fact that several of our GONG+ tables of frequencies were only computed for degrees ranging up to 800. Another alternative is that perhaps the mechanism which causes the $p$-mode frequencies to shift in response to changing levels of solar activity might saturate at the relatively high levels of activity encountered during 2001 in comparison with the much lower levels of activity which corresponded to our 1996 MDI frequency tables.

5. CONCLUSIONS

In spite of the fact that this study did not confirm the larger regression slopes found by Rhodes et al. (2003), we still believe that the keys to resolving the current controversy over the mechanism of the frequency shifts are the use of short time series, including both the high-frequency and high-degree modes. Intercomparisons of different sets of $p$-mode frequencies obtained from the GONG+ 2001 data, show that frequencies above 5000 $\mu$Hz are anti-correlated with changes in solar activity and they are more sensitive to changes in activity than the frequencies below 4000 $\mu$Hz. Also, the different sets of frequencies of both the intermediate- and high-degree modes have high enough signal to noise ratios that we have been able to compare time series as short as three days in duration. It will be desirable to study additional 3-day runs, as well as one-day runs in the future.

ACKNOWLEDGEMENTS

This work utilizes data obtained by the Global Oscillation Network Group (GONG) project, managed by the National Solar Observatory, a Division of the National Optical Astronomy Observatories, which is operated by AURA, Inc., under a cooperative agreement with the National Science Foundation. The portion of this research which was conducted at USC and at the Technical University of Munich was supported by NASA Grants NAG5-8021 and NAG5-8545 to USC. JR is grateful to both R. Bulirsch and P. Rentrop for their generous support and hospitality.

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