SIGNATURE OF THE SOLAR CYCLE IN THE LOW DEGREE P-MODES USING MARK-I

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ABSTRACT

High quality observations of the low degree p-modes exist for almost two complete solar cycles using the solar spectrophotometer Mark-I, located and operating at the Observatorio del Teide (Tenerife, Spain). In this work, the observations available have been re-analyzed over a much wider time interval than before. We analyze the time variation of the yearly frequency shift and its frequency dependence. This information will be used in order to average annual power spectra by removing the effect of the solar cycle. Using this average power spectrum, a new estimate of the rotational splittings is attempted.

1. INTRODUCTION

Understanding the well known solar variability is one of the major goals of solar physics. In the last years, the helioseismic data, by means of the frequency shifts of solar p-modes, have demonstrated to be very sensitive to the solar activity cycle. In particular, the existence of a positive shift of $\sim$0.4 μHz, peak-to-peak, with the solar cycle is very well known (Régulo *et al.* 1994, Jiménez-Reyes *et al.* 1998).

The spectrophotomer Mark-I, has been collecting solar observations for almost two complete solar cycles. The available database, one of the longest for low degrees, could be used to measure the mode parameters. However, the variation of the central frequency is an important effect which should be taken into account in order to use long time series.

In this work, we have analyzed the time variation of the frequency shift and its frequency dependence. Using this information we are able to average the annual spectra which is then fitted in order to measure the mode parameters, specially the rotational splittings.

2. ANALYSIS OF THE ANNUAL TIME SERIES

The data used in this work come from the observations carried out at the Observatorio del Teide for about 15 years, from 1984 to 1999. The observations consist of daily measurements of the solar radial velocity obtained with the Mark-I resonant scattering spectrometer. Briefly, after calibration and detrending, daily velocity residuals were joined in consecutive 360 days leading to a total of 30 time series with 6 months in common between consecutive series. The corresponding power spectra were calculated for each one of the time series.

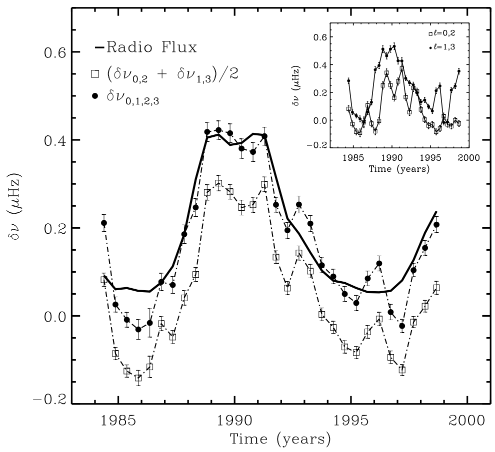

Figure 1. Time variation of the frequency shift for low degree.

In order to determine the frequency shift, all the power spectra have been cross-correlated using the same reference. The position of the main peak can be measured in different ways. Here, we use the fact that the cross-correlation between Lorentzian profiles is an other Lorentzian profile which can be used to calculate the central frequency by a least squares minimization.

The low degree modes are asymptotically equal spaced in frequency. This can be used to split in two the original spectrum, one containing only peaks with even degrees and the other containing only peaks corresponding to odd degrees. Then, the same procedure as explained above was applied to calculate the frequency shifts.

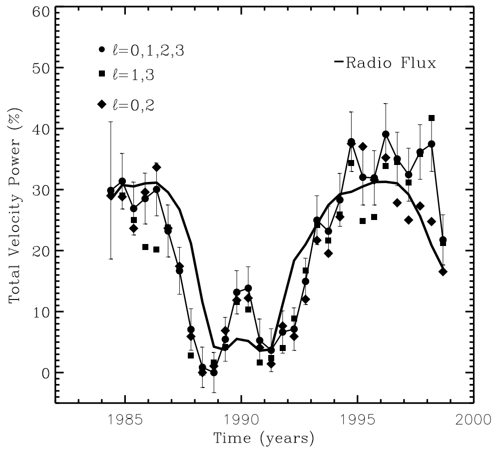

Figure 2. Time variation of the total velocity power defined as the area under the main peak of the cross-correlation function.

In the Figure 1 we show the integrated frequency shift between 2.5 and 3.7 mHz. The results corresponding to ℓ=0,2 and ℓ=1,3 have been plotted in the subplot at the top-right corner and its averaged (shifted -0.1μHz) is shown in the main figure, which agrees very well with the integrated signal. The amplitude, peak-to-peak, of this changes is around 0.4μHz, as we expected.

The best fit of the annual radio flux has also been plotted to show the good correlation between the solar activity and the frequency shift. Using annual time series we have reduced the high frequency signal in the variation of the frequency shift, keeping the long term behavior. Thus, the correlation levels between these parameters are clearly close to 1.

We have also calculated the total velocity power defined here as the area under the main peak of the cross-correlation function. Once the main peak is fitted as a Lorentzian profile, the area can be calculated from the amplitude and linewidth.

The first demonstration of the variation for the velocity power for all measured p-modes with the solar activity was reported by Pallé *et al.* (1990) where an increase of 30 to 40 %, anti-correlated with the solar activity cycle, was found. Afterwards, Anguera *et al.* (1992) found similar results following different techniques. Those results were interpreted in terms of a change in the efficiency of the excitation of such modes. Other possibility should be the absorption of mode power by magnetic structures like sun spots, active regions, etc. However they represent a small influence and it cannot explain totally such high ratio.

In the Figure 2, we present the time variation of the total velocity power. Again, we show the radio flux scaled which denotes here the behavior of the solar activity cycle. From the figure, we are able to see the variation between minimum and maximum of the solar cycle is around 35% which agrees with previous results. Moreover, it is clear the high anti-correlation with the solar cycle, thus the velocity power decreases when the activity increase. The corresponding variation for the odd and even degrees are very similar and they are shown as well in the same figure.

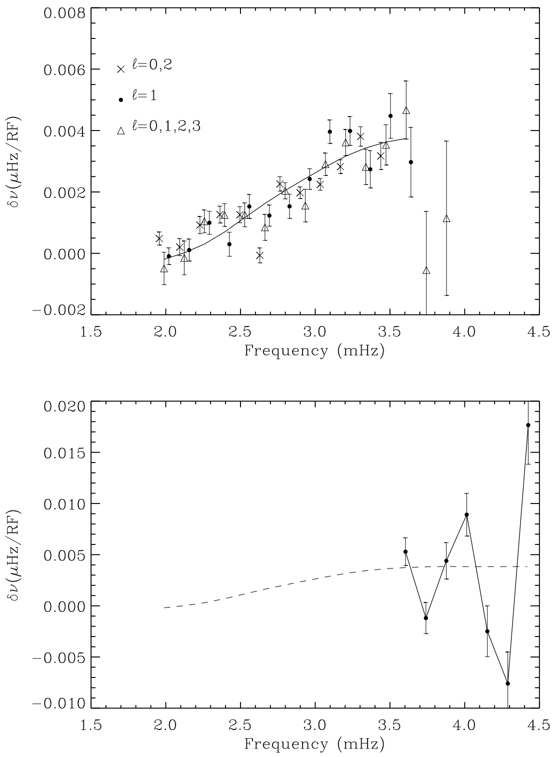

Figure 3. Variation of the dependence of the frequency shift like a function of the frequency.

Before completing this section, we analyze the frequency dependence of the frequency shift. Thus, we split each one of the spectra in regions of 135μHz which contain a set of modes ℓ=0,1,2 and 3. Then, every region is cross-correlated with the same reference and finally the method explained above is used to calculate the frequency shift. The results can be seen in the Figure 3 which have been plotted together with the best fit of the inverse mode mass averaged for low degree and over the same region in frequency. As we can see, the frequency shift can be reproduced very well by the inverse mode mass, which means that the origin of this variation should be close to the solar surface. This variation in the frequency dependence agrees very well with earlier studies carried out at higher degree (Libbrecht and Woodard, 1990)

The results are in good agreement with the individual fittings carried out by Jiménez-Reyes (2000) shown as well in the figure. He has applied similar techniques at high frequency as well, where a strong fluctuation of the frequency shift appears, as we can see in Figure 3 (bottom).

3. THE ROTATIONAL SPLITTINGS

One way to increase the signal to noise ratio is to average spectra. Nevertheless, it cannot be done directly because the central frequency of the acoustic modes are expected to change. In that case, the linewidth would be bigger and the structure of the peaks are not well defined leading to wrong fits.

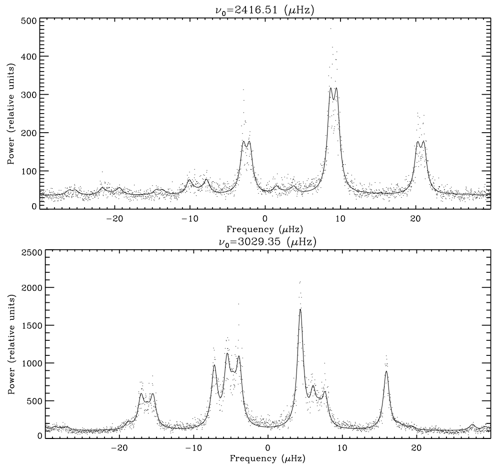

Figure 4. Examples of two sections of the averaged spectra. In the top a piece of the spectra containing a couple of odd modes ℓ=1,3 is successfully fitted (solid line). In the lower figure, other piece of the averaged spectra is showed, in this occasion for ℓ=0,2.

Thus, before averaging spectra, we need to shift them in order to remove the effect of the solar activity. We studied in the last section that the central frequency of the acoustic modes changes are a function of two parameters: time and frequency. The time dependence can be expressed as a function of the radio flux for instance, thanks to the good correlation between them. The behavior with the frequency is expected to be very soft, being null at low frequency and increasing slowly at high frequency. We have also shown that this dependence can be expressed as a function of the inverse of the mode mass. In brief, our 30 spectra covering 15 years of the solar cycle have been shifted and then averaged using the information obtained about the behavior of the frequency shift.

The Figure 4 shows two different pieces of the averaged spectrum, once each one of the yearly spectra has been shifted to remove the effect of the solar activity. In the top, a couple of odd modes and the best fit of our model is plotted while in the bottom a group of even modes and its best fit is shown. Note, that the fine structures are quite easy to identify. So, the rotational splittings is in all the cases very clear allowing us to fit the mode parameters easily. The sidebands emerge also from the noise and it was necessary to consider them as well in the model.

The statistic of the power spectra is expected to be χ^2 with 2 degree of freedom. However, when many spectra are averaged the statistic becomes Gaussian, especially when the number of spectra averaged is large like in our case. Thus, we use a Marquard-Levenberg method for this work to perform a non-linear least squares minimization, and the formal errors bars are the output of the program.

The advantage of the technique proposed here is in the fact the signal is cleaned from the re-excitation component and thus become less spiky. In addition, structure from the acoustic modes emerges from the noise allowing a better identification of the signal, which is specially important for ℓ=3 due to the low sensitivity of the instrument to that degree. However, for the same reason the second sideband due to modulation of one day, appear clearly in the spectra.

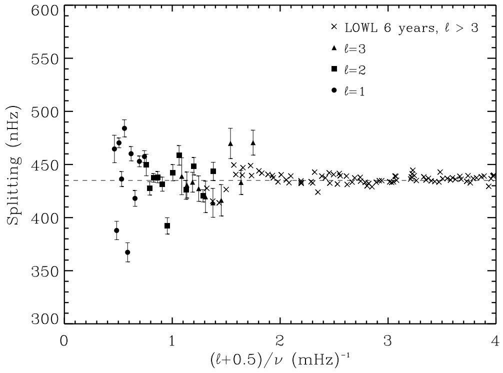

Figure 5. Rotational splittings for low degree ($\ell \leq 3$). The crossed represent the averaged a_1 coefficient using 6 years of LOWL data. The dashed line shows a constant rotation rate at 435nHz.

Table 1. Low degree p-mode splittings in nHz.

n	ℓ=1	ℓ=2	ℓ=3
11		443.47± 8.60	
12		420.51± 5.75	470.57±11.74
13	457.48± 5.51	448.36± 8.23	433.10±11.36
14	452.92± 5.10	426.11± 8.23	469.85±14.29
15	418.08± 7.45	458.62± 9.19	416.30±14.76
16	460.14± 6.73	442.28± 7.65	413.91±13.63
17	367.32± 9.00	392.20± 7.69	419.56±14.83
18	484.02± 8.06	431.51± 6.64	427.28±12.00
19	436.31± 7.02	438.07± 5.33	433.35± 9.37
20	470.37± 4.64	437.41± 4.03	430.67±12.26
21	387.85± 8.69	427.49± 6.26	438.90±17.38
22	464.63±12.93	449.52±10.16	
	447.54±2.11	433.41±1.92	435.90±3.99

Adjacent degrees have been fitted together using a window 60μHz large, centered at halfway between the central frequency of both modes. The linewidth and the level of background is supposed to be the same. It is necessary due to the distance of the these modes, which decrease at higher frequency. This difficulty becomes more critical in our case due to the presence of sidebands.

Finally, we present in Figure 5 the rotational splittings calculated in this work plus the average of 6 years using LOWL data (Jiménez-Reyes 2000), for degree above four. A straight line at 435 nHz has been drawn over the data. The rotation rate seems to be constant, however at higher depth, there is a certain scattering but no clear trend can be seen. The successful fits are also tabulated in the Table 1. The last row represents the weighted mean for each degree. All these results lead us to think that the rotation rate in the core is very likely to be constant and equal to the rest of the radiative part, although some dispersion remain at very low turning point.

We have compared our results which those obtained by Bertello *et al.* (2000) and Chaplin *et al.* (1999). The first work describe the analysis carried out on a time serie from 759 days of calibrated disk-averaged velocity signal provided by two different instruments, GOLF and MDI, both on board the Solar and Heliospheric Observatory (SOHO). This data begin close to the solar minimum in 1996 May 25, where any important change in the central frequency of the acoustic modes is expected, and finish in 1998 June 22. Moreover, they have considered two different kind of fits, one using the typical Lorentzian profile and other which introduce possible asymmetries.

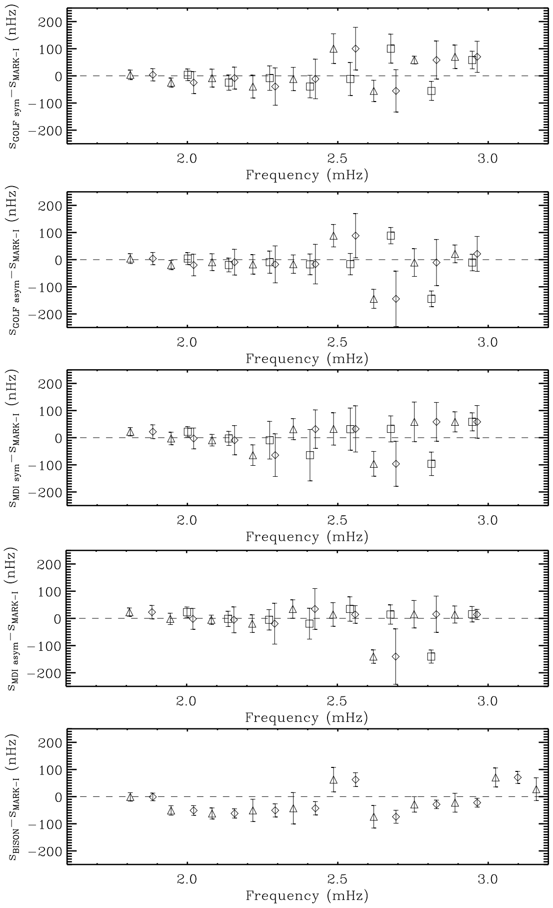

Figure 6. Differences of the rotational splittings in nHz between others works and those measured in the present analysis.

The second work represents the last published splittings measured for BISON team. They come from of a 32-month power spectrum generated from velocity signal collected between 1994 May 16 and 1997 January 10. Again, the period considered is near the solar activity minimum. In both works the duty cycle is higher than in our case, being close to 100% for GOLF and MDI.

The differences of our work with those works are shown in the Figure 6. There are significant differences between our results and those obtained by BISON group. Their splittings are in general lower than our results. However, this does not appear in the comparison with GOLF or MDI data, for which the differences are more random around zero with a small scattering, especially at low frequency. These differences are specially small when a asymmetric profile were considered.

4. CONCLUSION

An analysis of the p-mode frequency shift over more than one solar cycle has been carried out. The time dependence of the frequency shift as well as its frequency dependence have been parameterized. Then, this information has been used in order to shift each one of the annual spectra, removing therefore the signature of the solar activity cycle.

The rotational splittings are in good agreement with those obtained by Bertello *et al.* (2000). Thus, the rotation rate is very close to 435 nHz like the rest of the radiative part. However, there is still some fluctuation at lower turning point. The comparison with the splittings measured by Chaplin *et al.* (1999) shows a significant difference.

The method presented here can be useful in the analysis of long time series, covering an important part of the solar cycle. Last but not least, if all the ground instruments (e.g. BiSON, IRIS, ECHO) are joined, then the quality and also the duty cycle of the time series will increase, reducing the systematic errors, allowing new perspectives in the analysis of the solar activity cycle using the frequency shift as a new solar index.

5. ACKNOWLEDGMENTS

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