VARIATIONS OF THE LOW l SOLAR ACOUSTIC SPECTRUM CORRELATED WITH THE ACTIVITY CYCLE

P.L. PALLÉ, C. RÉGULO, T. ROCA CORTÉS
Instituto de Astrofisica de Canarias
38200 La Laguna. Tenerife
Spain

ABSTRACT. Solar cycle variation of the frequencies and of the power of solar acoustic oscillations are investigated. Integrated sunlight data from 1977 to 1988 obtained at the Observatorio del Teide (Izaña, Tenerife), using a resonant scattering spectrophotometer, is analyzed in 60 day time strings and their power spectra are calculated from 2 to 3.8 mHz. To study the frequency variation, each power spectrum is cross-correlated with the one corresponding to the 1981 series and the shifts of the centroids of the cross-correlation peaks are calculated. The results show a clear variation in frequency of the cross-correlation peaks of $-0.37 \pm 0.04\,\mu$Hz peak to peak as solar activity cycle goes from maximum to minimum. Moreover, this effect is found to depend on the l value of the modes, being absent for $l = 0$ and of $0.42 \pm 0.06\,\mu$Hz for $l = 1$. These results can be interpreted as an amplitude modulation between modes of the same multiplet, probably as a consequence of the action of strong magnetic fields. As low l modes penetrate deeply into the Sun's interior, these observations suggest changes in its structure correlated with the solar activity cycle. When the power of the modes is calculated, using the same series as before, and its change along the solar cycle is studied, a variation of $\sim 40\%$ is found, the power being higher when solar activity is at its minimum. If this effect is independent of the l value of the p-modes, the results can be interpreted in terms of a change in the efficiency of the excitation mechanism of such modes. Indeed, if turbulent convection is such a mechanism, a change in the characteristic size of the granulation would account for the observed effect. Alternatively, another explanation could be a selective change in the efficiency of the excitation and/or damping mechanisms of the $l \leq 3$ modes in front of other l value modes.

1. Variations of the frequencies of low degree acoustic modes

Velocity data obtained from 1977 through 1988 is analyzed to look for variations in the frequencies of the acoustic p-modes (Pallé et al,1989). No useful disk-integrated light observations are available in 1979 and, in 1983, the observations were somewhat noisy, due to problems with the electronics. Data taken each day is individually analyzed and their residuals are joined together in sets of time strings of 60 continuous days (see Table 1). Power spectra are calculated using an interactive sine wave procedure; the amplitude squared and phase for each frequency, from 2 to 3.8 mHz, are calculated at intervals of 0.1 μHz. Then, the background noise of the spectra is calculated and subtracted. To compare the different power spectra, a cross-correlation technique is used.

G. Berthomieu and M. Cribier (eds.), Inside the Sun, 349–355.

https://doi.org/10.1017/S0252921100068056 Published online by Cambridge University Press

Years	Period of Year		Useful-days	Duty cycle
1977	12- 7; 25- 8	*	38	30%
1978	31- 7; 9- 9	*	25	25%
1980	21- 7; 17- 8	*	28	40%
1981	25- 6; 22- 8	*	56	42%
1982	11- 5; 7- 7		54	39%
1982	30- 6; 28- 8	*	58	40%
1982	8- 7; 3- 9		56	39%
1983	4- 6; 2- 8	*	52	35%
1984	1- 5; 29- 6		55	37%
1984	12- 5; 8- 7		55	37%
1984	30- 6; 28- 8	*	59	42%
1984	10- 7; 7- 9		58	40%
1984	11-11; 9- 1		48	24%
1985	31- 3; 29- 5		46	30%
1985	28- 5; 23- 7		55	40%
1985	30- 6; 28- 8	*	53	35%
1985	26- 7; 18- 9		50	35%
1985	15- 9; 9-11		43	23%
1986	1-12(85);25- 1		40	21%
1986	8- 2; 31- 3		40	28%
1986	2- 4; 31- 5		50	33%
1986	16- 7; 4- 9	*	51	40%
1986	1- 9; 31-10		52	28%
1986	1-11; 31-12		45	23%
1987	3- 1; 28- 2		44	26%
1987	1- 3; 30- 4		37	20%
1987	1- 5; 30- 6		52	34%
1987	8- 6; 6- 8	*	54	40%
1987	1- 8; 30- 9		38	20%
1987	1-10; 30-11		35	13%
1988	12-12(87);31-1		38	24%
1988	1- 2; 31- 3		36	17%
1988	1- 4; 31- 5		52	35%
1988	1- 6; 31- 7	*	55	40%

TABLE 1.- *Time series (maximum 60 consecutive days long) analyzed in this work; an asterisk (*) denotes the summer series whose cross-correlation functions are shown in Fig. 1. The duty cycle is calculated as the percentage of hours of observations as opposed to total possible hours of observations (including nights).*

The power spectrum of 1981 data series is used as the reference against which all the others are cross-correlated.
The cross-correlation functions obtained using the summer months of each year are plotted in Fig. 1. A displacement of the cross - correlation peak of all functions to the left can be seen. To measure the position of the cross-correlation peak, the centroid is used. In Fig. 2 the centroids from all the series in Table 1 are shown. A variation from year to year is clearly evident. Taking the difference between the maximum (around 1981) and the minimum (1985/86), a peak to peak variation of $-0.37 \pm 0.04\,\mu$Hz is found.
In order to find if this result changes with the degree of the modes, four spectra were obtained from each calculated power spectrum, each one containing only the information around the "isolated" first order sideband of modes $l = 0, 1, 2$ and 3. The same procedure as before has then been repeated. The resulting centroids are presented in Fig. 3. The peak to peak variations are : -0.04 ± 0.1, -0.42 ± 0.06, -0.38 ± 0.14 and $-0.47 \pm 0.1\,\mu$Hz for $l = 0, 1, 2$ and 3. Thus, unlike $l > 0$ modes, $l = 0$ modes show very little, or no, trend at all; the mean values of all available points for l_0 is of $-0.18 \pm 0.03\,\mu$Hz.

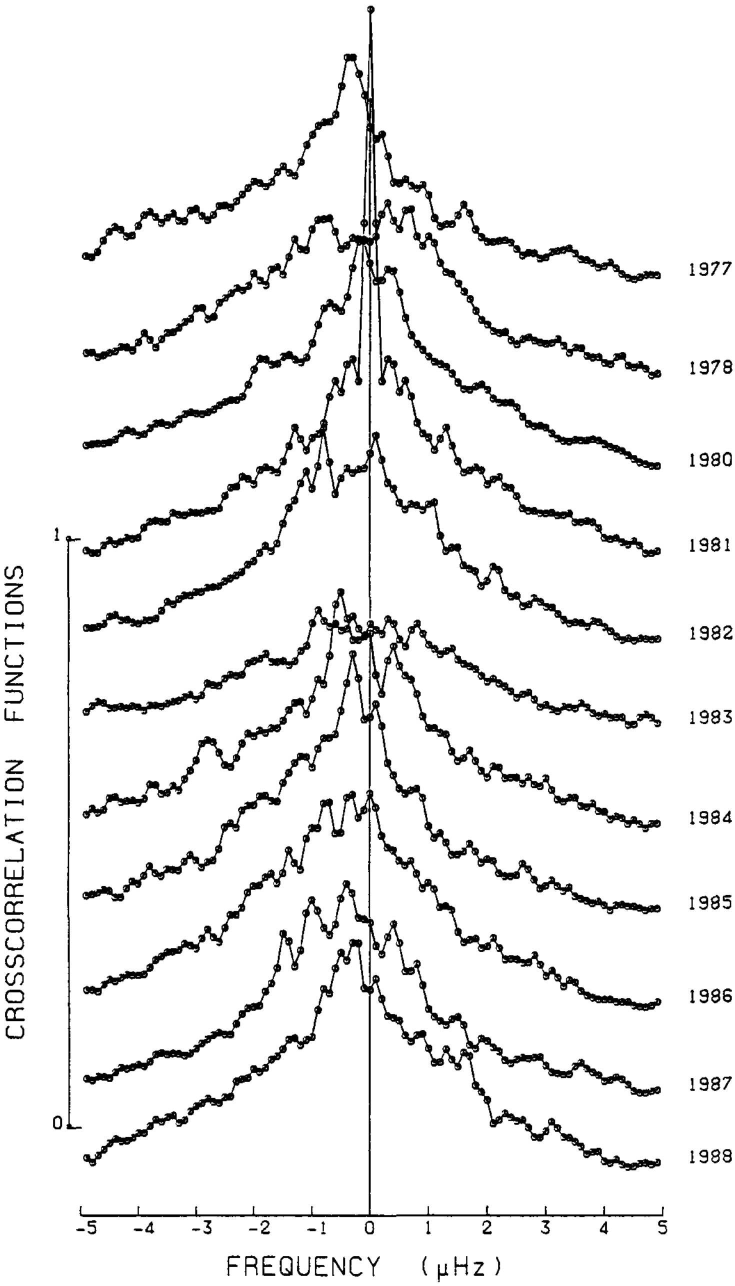

FIGURE 1.- *Cross-correlation functions of the power spectra of the summer months series for each year (see Table 1), with respect to the one for summer 1981.*

The dependence of this variation on the l value of the modes, the variation being absent for $l = 0$, suggest that other interpretations than merely a shift of frequencies in the acoustic mode spectrum across the solar cycle are plausible: an amplitude modulation between modes of the same multiplet and/or an asymmetric change of the splitting (probably due to magnetic fields) through the solar cycle. Therefore, the results found might come partially from an actual dynamic effect of an internal field (which would also shift the $l = 0$ mode), amplified due to the solar cycle amplitude modulation, as unresolved magnetically split lines weight differently to the rotationally split ones. A straightforward numerical simulation of such an explanation has been performed; it is found that a 25% amplitude variation of the modes within a multiplet across the solar cycle would yield the observed results.

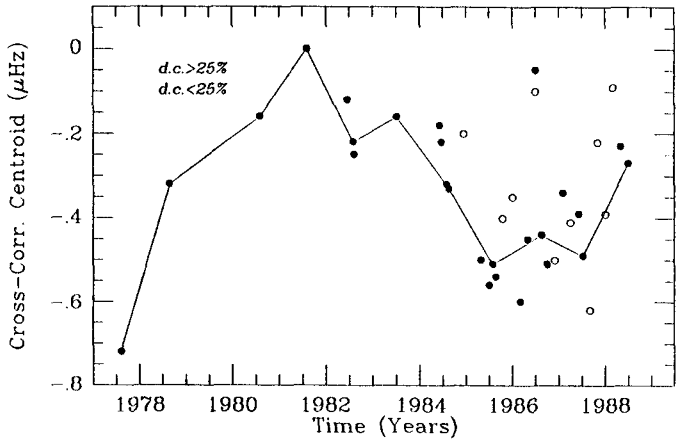

FIGURE 2.- *Centroids calculated from the cross-correlation functions of power spectra of all available data (see Table 1). Unfilled circles stand for those series with less than 25% duty cycle.*

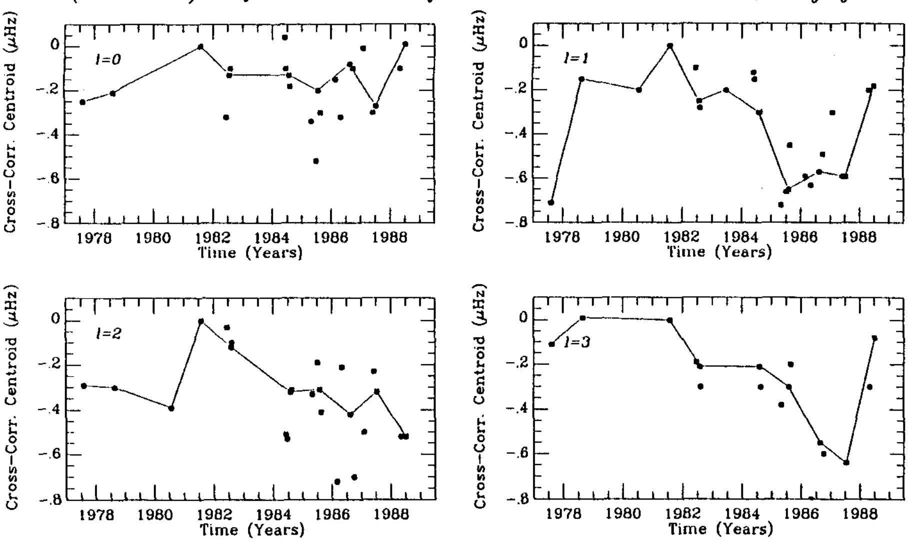

FIGURE 3.- *Centroids calculated from the cross-correlation of power spectra for: a) l = 0, b) l = 1, c) l = 2, d) l = 3, with respect to 1981. Each spectrum used keeps only the information around the first "isolated" sideband of each mode.*

https://doi.org/10.1017/S0252921100068056 Published online by Cambridge University Press

2. Variation of the power of low degree acoustic modes

Using the same 60 day time series already studied (see Table 1) the power in each mode has been calculated and its possible variation along the solar cycle investigated. The power, rather amplitude squared, has been calculated as follows:

$$P = \sum_{l=0}^{2} \frac{P_l}{S_l} = \sum_{l=0}^{2} \frac{1}{S_l} \sum_{n=13}^{25} \sum_{i=-k}^{k} (A_{i,l,n}^2 - A_{noise}^2)$$

where:

$A_{i,l,n}$ is the amplitude at frequency ν_i , around a peak representing the mode of degree l and order n, as found by Jiménez et al (1988).

A_{noise} is the mean amplitude of the noise level for 136μ Hz around a given set of peaks.

k has been set at $2\delta\nu$, where $\delta\nu$ is line width as measured in Elsworth et al (1989).

S_l is the sensitivity of the integrated sunlight velocity measurements as defined in Pallé et al (1989).

n stands for the order of the modes.

The values found from P and P_l for $l = 0$ to 3, are shown in Fig. 4 and 5. It must be born in mind that, in these 60 day series non negligible first order side bands exist for every peak present in the spectra, due to the observing window function. Moreover, the worse the duty cycle, the more power goes into the sidebands. This explanation is important, because due to the separation between l_0 and l_2 ($\sim 9\,\mu$Hz), its relative power is, 1:1 and the rotational splitting for l_2 modes some of the sidebands power can contribute to the power per mode calculated. As far as $l = 1$ and 3 are concerned, this problem is somewhat less severe because their separation is $\sim 15\,\mu$Hz and their relative power is $\sim$ 10:1; therefore, the most reliable measurement is for $l = 1$ where this effect is very small. From the results shown in Fig. 4 and 5 a $\sim$ 40% variation can be deduced, well correlated with solar activity cycle, the power being higher when the solar activity is at minimum, confirming a previous trend found in Jiménez et al(1988).

The interpretation of this effect could be attributed to the absorption of mode power by magnetic structures (sunspots, active regions, etc...) already found for higher l modes by Braun et al (1988), but it seems unlikely. The reason being that, if magnetic structures absorb the same amount of p-mode power for $l \leq 3$ as for higher l modes, which is $\sim$ 50%, then, since at the maximum of solar activity, the surface covered by active regions can be 10% at most hence the power absorbed by them would be less than 5%, which is clearly not enough to explain the observed effect.

Therefore, it is more likely that changes in the efficiency of the excitation mechanism of such modes could be the cause. Assuming turbulent convection to be the responsible for exciting these modes with energies $E \sim c^2 \rho L^2 H$(Libbrecht ,1988), where ρ is the density, c the sound speed, H the scale height and L the characteristic size of the granules, then a maximum variation of $\sim$ 20% in L along the solar cycle would account for the observed effect. Observations of such variations have already been made by Muller and Roudier (1985) with similar numerical results (in fact their observations would imply a change of only 10% on L).

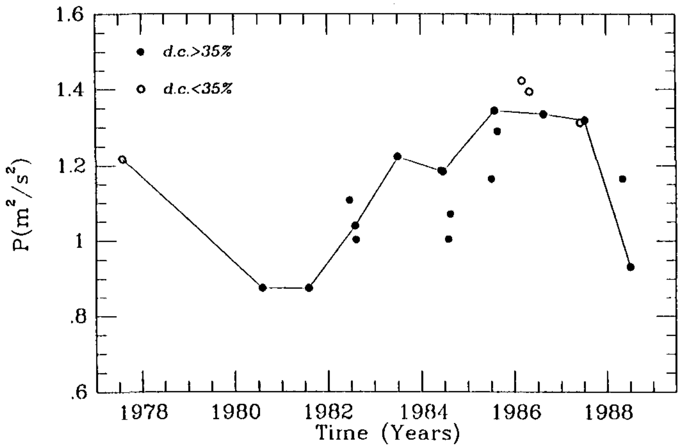

FIGURE 4.- *Power per mode summed over all modes, with* $l = 0, 1, 2$ *and within the interval (2.00, 3.84) mHz, multiplied by its sensitivity function (see text). A line joins the values corresponding to summer series (see Table 1).*

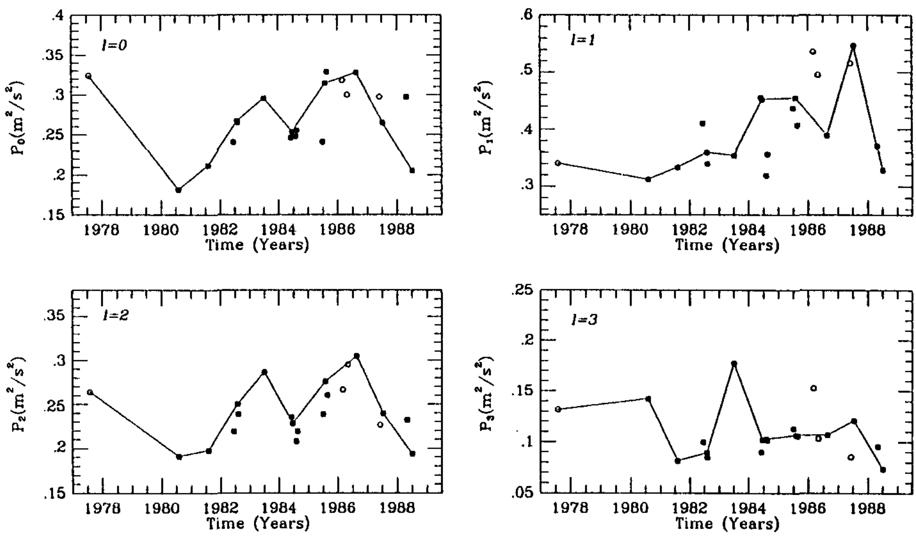

FIGURE 5.- *Power per mode summed ever all modes within the interval (2.00,3.84) mHz and different* $l = 0, 1, 2$ *and* 3*. The symbols are the same as in Fig. 4.*

https://doi.org/10.1017/S0252921100068056 Published online by Cambridge University Press

References

- Braun D.C., Duvall Jr. T.L., La Bonte B.J., (1988),'Acoustic absorption by sunspots', Ap. J.,**335**, 1015.
- Elsworth Y., Isaak G.R., Jefferies S.M., McLeod C.P., New R., Pallé P.L., Régulo C., Roca Cortés T.,(1989), 'Linewidth of low degree acoustic modes of the Sun'. M.N.R.A.S., (in press).
- Jiménez J.A., Pallé P.L., Pérez J.C., Régulo C., Roca Cortés T., Isaak G.R., McLeod C.P., van der Raay H.B.,(1988) in J. Christensen-Dalsgaard and S. Frandsen (eds.) 'Advances in Helio and Asteroseismology', Reidel, 205.
- Libbrecht K., (1988). 'The excitation and damping of solar p-modes'.in E.J. Rolfe (ed.) 'Seismology of the sun and sun-like stars', ESA SP-286,3
- Muller R. and Roudier T., (1984).'Variability of the structure of the granulation over the solar activity cycle' in 'The Hydromagnetics of the Sun",ESA SP-220, 51.
- Pallé P.L., Régulo C. and Roca Cortés T.,(1989), 'Solar cycle induced variations of the low l solar acoustic spectrum', Ast. & Ap.(in press).
- Pallé P.L., Pérez Hernández F., Roca Cortés T., Isaak G.R., (1989), ' Observation of solar p-modes with $l \leq 5$ '. Astron. & Astrophys. , (in press)