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Frequencies and splittings of low-degree solar *p* modes: Results of the Luminosity Oscillations Imager

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Abstract. The Luminosity Oscillations Imager is a part of the VIRGO instrument to be flown aboard the Solar and Heliospheric Observatory in mid 1995. Using a ground-based version of the instrument, we have detected low-l modes with a time series spanning 163 days. The low resolution capability of the instrument allows the identification of individual tesseral orders for $l = 2$ to 5. The data reduction method prevents from observing the $l = 0$ modes, and reduces the amplitude of the $l = 1$ modes with $m = \pm 1$. The frequencies and, for the first time, the linear component of the mode splitting (a_1) are given for l=2 to 5 for each order n. The frequencies and the a_1 are obtained by fitting simultaneously the $2l + 1$ spectra using maximum likelihood estimators. The splittings are compared with other published values.

Key words: solar oscillations - p modes - internal rotation

1. Introduction

Helioseismology is a powerful tool to infer the internal structure of the Sun. Over the past two decades, various apparatus reported on the detection of global solar p modes. High resolution imaging instruments can detect degree down to $l = 3$ (Harvey, 1988) while separating the individual tesseral orders m, allowing to measure the splitting of the modes. Unfortunately the instability of these instruments prevents to detect modes with $l < 3$. Integrated sunlight instruments do not have any resolution, but they can detect degree from $l = 0$ to $l = 3$ (Harvey, 1988). The various m components are not all detected and are mixed in the power spectra, making difficult the determination of mode splitting at low l. Various attempts to measure those splittings are starting to give consistent results (Jiménez et al, 1994; Loudagh et al, 1993; Toutain and Kosovichev, 1994). Nevertheless, the rotational splitting given by these authors is an average over various n and l.

It is hoped that with the Solar and Heliospheric Observatory (SOHO), long observations combined with the absence of atmospheric noise will lead to significant improvements in the knowledge of the internal solar rotation (Domingo and Poland, 1989). From the ground, it has been proposed by Tomczyk et al (1994b) to observe the splitting of low-l modes using an imaging instrument with a very stable zero point. Their seminal work gave us the momentum for trying to detect from the ground the mode splitting with the Luminosity Oscillations Imager (LOI). The LOI was built by the Space Science Department of the European Space Agency as a contribution to the VIRGO instrument (Variability of Solar Irradiance and Gravity Oscillations), one of the helioseismology instruments of SOHO. After the completion of the flight programme, we installed in May 1994 the Qualification Model of the LOI at the Observatorio del Teide (Izaña, Tenerife) for detecting in intensity low-l p modes. Due to the atmospheric noise, the detection of p modes in intensity is difficult (Jiménez et al, 1987; Andersen and Domingo, 1988). Nevertheless, the successful observation of low-l p modes by the LOI leads to improvement in the determination of the rotational splitting of low-l modes. Here we present new measurements using a technique to fit the spectra that was developed independently of Tomczyk et al (1994a). The frequencies and, for the first time, the a_1 component of the splitting are given for each n and l.

In this letter, we describe firstly the LOI instrument and secondly how the data were obtained and reduced. In

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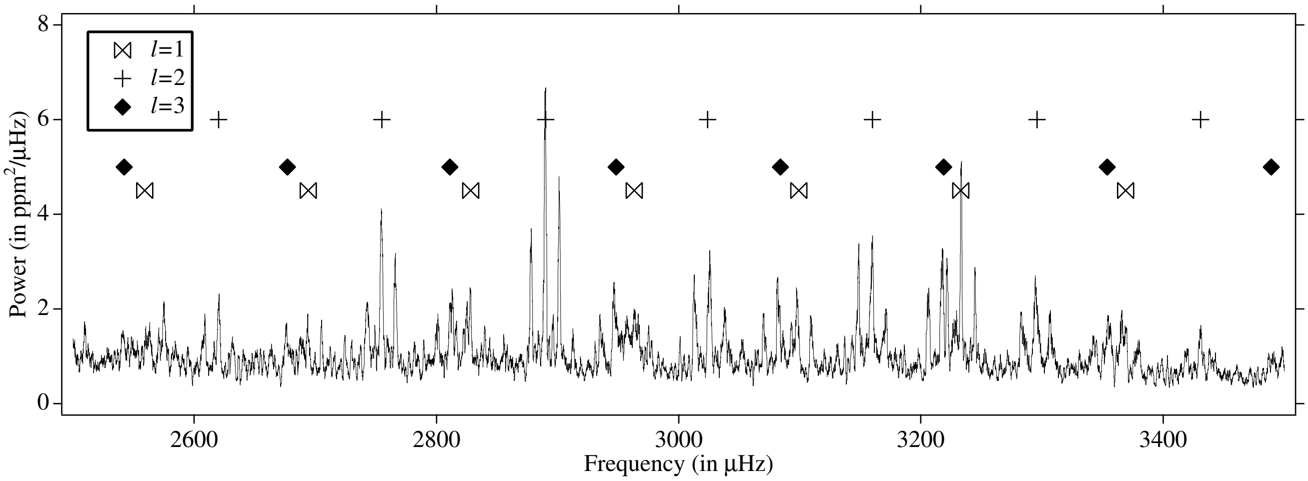

Fig. 1. Power spectrum for the $l = 1, m = 0$ optimal filter, smoothed to 21 points to enhance the modes. The frequency resolution is 0.071 μHz. Each mode and its two aliases can be identified. In addition, the spatial sidelobes are clearly visible; they are the $l = 2, m = \pm 1$, and the $l = 3, m = 0$ modes

the third section, we expose how the spectra were analysed. In the last section, we compare our results with other available values and then conclude.

2. Description of the LOI instrument

The design of the LOI instrument was an original idea of Andersen et al (1988). It consists of a Ritchey-Chrétien telescope (f=1300 mm) imaging the Sun through an 5-nm passband interference filter at 500 nm. The image is projected on a photodiode array detector built to our specifications (Appourchaux et al, 1992). The detector is made out of 12 scientific pixels and of 4 guiding pixels. The shape of the scientific pixels are trimmed to detect low degree modes for $l < 7$ (Appourchaux and Andersen, 1990). The guiding pixels are 4 quadrants of an annulus with an inner and outer radius of 0.95 and 1.05 solar radius, respectively. The error signals for the guiding servo are the differences between two opposite pixels. The error signals are fed back to two piezoelectric actuators that move the secondary mirror around its vertex. The actuators provide both the coarse and fine pointing; the total range of the Qualification Model is $\pm 5'$ with a 0.2" precision; the 3db bandwidth of the servo control is 10 Hz. The current of each scientific pixel is amplified and digitised using Voltage-to-Frequency Converters (VFCs). The current of each guiding pixel is amplified and digitised using A/D converters. The 12 scientific pixels are read simultaneously while the 4 guiding pixels are read sequentially. The sampling time of the instrument is 53.687523 s. The integration time of the scientific pixels is the same as the sampling time. The integration time of the guiding pixels is about 2 s. The instrument is controlled with a PC and all scientific and housekeeping data are stored on a hard disk.

3. Observation and data reduction

The LOI instrument was installed on an equatorial mount on May 2, 1994 in Tenerife. The time series analysed here starts from May 2 and ends on October 11. The duty cycle is about 33 %. Most observations were performed when the Sahara desert blows sand in the sky of Tenerife, and therefore lowers the transparency and increases the scattered light. The clock of the PC was drifting from day to day. This drift was daily measured and if necessary the PC clock was readjusted. The observed stability of the guiding was about 0.2-0.4". This is an upper limit since the atmospheric transparency changes as the guiding pixels are read. The LOI was not aligned with the solar rotation axis and the Sun was rotating from day to day with respect to the detector.

The data reduction was done in three steps. Firstly, we correct the pixels for the fluctuations in the atmospheric transparency; this is done by dividing, at a given time, each pixel by an average over the 12 pixels. Thanks to the coherence of the atmosphere over the solar disk, this reduces by a factor 20 the main atmospheric effect. Secondly, we correct the pixels for their different sensitivity and of the differential extinction; this is done by dividing each pixel by a running mean of the pixel. The running mean is a gaussian filter; the frequency cut-on of this filter is 0.5 mHz. For each pixel, the lowest σ of the series is used to remove spikes greater than 5 σ; the spikes are replaced by zeros. Thirdly, the time series for each pixel are resynchronised every day using a linear interpolation. No other instrumental correction are performed. These data are used for computing the time series for a given l, m mode.

4. Frequencies and splittings

The optimal linear combination of the pixels to obtain a given l, m mode was reported by Appourchaux and Andersen (1990). Here we used their optimal filters computed for a perfect LOI detector having neither tracks nor guiding pixels. This approximation has proven to be sufficient for our purpose and correct optimal filters are being computed for the SOHO instrument. Since the Sun rotates with respect to the detector (the P and B angles are not negligible) the optimal filters are updated every week and a linear interpolation provide the daily optimal filter. If one were to neglect this image rotation, one would see the effect by an increased cross talk between the modes. For the l, m mode to be analysed, a single time series is obtained by computing the weighted average of the 12 pixels using the optimal filter of the l, m mode. The optimal filters are complex and allow to separate the prograde and retrograde modes in the Fourier space. To minimise the atmospheric noise, the time series for the given l, m mode are weighted by the daily variance; this provides a significant improvement in the power spectra. The time series are normalised to take into account the weighted window function. The frequency resolution of the power spectra is 0.071 μHz.

Figure 1 shows the power spectrum for the $l = 1, m = 0$ optimal filter; modes with $l = 1, 2$ and 3 are clearly detected with amplitudes of about a few part-per-million (ppm). The noise level is about 0.8 ppm$^2/\mu$Hz which is about a factor 4 higher than the noise obtained from space by IPHIR. The signal-to-noise ratio in the power spectra ranges from 1 to 4. It must be pointed out that contrary to what has been reported by Pallé et al (1993), the $l = 1, m = 0$ modes are detected by Tomczyk (1994) and by us. Figure 2 shows a $m - \nu$ diagram for an $l = 2$ mode; the rotational splitting is also clearly visible. The data reduction procedure prevents from detecting the $l = 0$ mode because this mode is filtered out when correcting for the fluctuations of the atmospheric transparency. For the same reason the $l = 1, m = \pm 1$ modes are attenuated by a factor of 4 in the power spectrum. In addition these modes are mixed in the power spectra because their relative phases are lost in the process.

In order to extract in the best way the information contained in the spectra, we chose to fit simultaneously the $2l + 1$ spectra of a given n, l mode using maximum likelihood estimators (MLE); this technique is also used by Tomczyk et al (1994a). The window for the MLE was 14.2 μHz centred on the frequency of the $m = 0$ mode. We assumed that the linewidth is the same for the $2l + 1$ components of an n, l mode; and that the frequency of an m component is $\nu_m = \nu_0 + m a_1$, where a_1 is the linear component of the splitting. The maximum likelihood technique is well known and its error propagation properties are well understood (Toutain and Appourchaux, 1994). The use of MLE leads to two major approximations. Firstly, it is assumed that in a power spectrum the frequency bins are independent of each other. This is not true as we have gaps in the data (Gabriel, 1994). Nevertheless, the method we used is much simpler than the method suggested by Gabriel (1994), and will not bias the estimate on frequency (Lazrek and Hill, 1992) and splittings. Secondly, we assumed that for a given l, the $2l + 1$ spectra are independent of each other. This is a very good approximation even if there is a crosstalk (due to the imperfect isolation of a given l, m mode) between the $2l + 1$ spectra. The effect of the crosstalk is to couple for a given n, l mode the m components with each other; this was taken into account in the analysis. Due to the small correlation between the $2l+1$ spectra, the error bars on the frequency and splitting will be slightly underestimated. The same underestimation happens if one uses the temporal sidelobes at 11.57 μHz: the error bars would be underestimated by about a factor $\sqrt{3}$. The correct treatment of the power spectra taking into account the statistical dependencies (frequency bins, temporal and spatial sidelobes) remain to be done using the method described by Gabriel (1994). However we believe that only the estimate of the

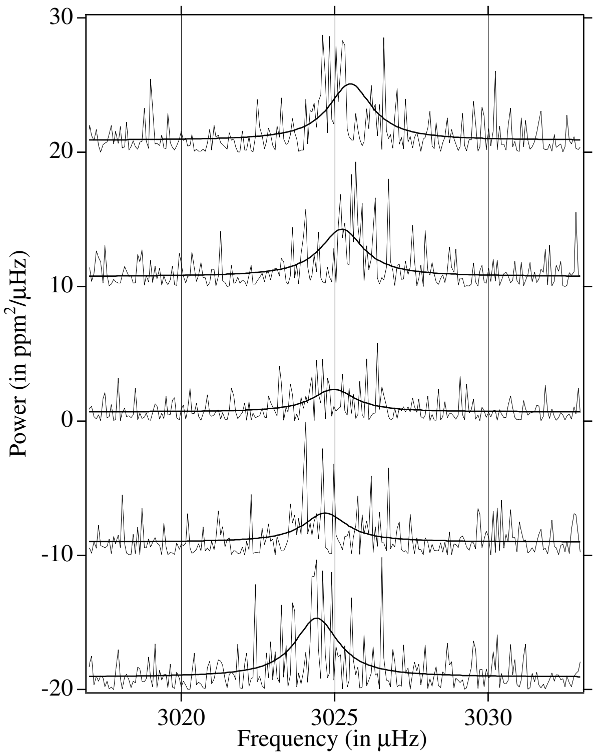

Fig. 2. $m - \nu$ diagram for the $l = 2, n = 20$ mode. The spectra are not smoothed. The fit for this mode are superimposed in bold

error bars on the frequency and splitting are biased, and not the values themselves. To minimise this bias, the error bars have been corrected at least from the crosstalk between the various m components. Table 1 and Table 2 summarise, respectively the frequencies and the splittings of the detected modes. In addition, an optimal weighted average (<>) of a_1 is given in Table 2.

5. Discussion and conclusion

For $l = 2$, we are in agreement with Elsworth et al (1994), and Toutain and Kosovichev (1994) (average over $l = 1, 2$: 440 ± 10 nHz, 452 ± 20 nHz respectively), and in disagreement with Fossat et al (1994) (low order modes: 499 ± 15 nHz); these 3 values represent an average of the splitting of sectoral modes, and should therefore be slightly higher than our a_1 by a few nHz (D.O.Gough, 1994, private communication). For $l = 3$, we are in disagreement with Fossat et al (1994) (low order modes: 463 ± 15 nHz). On the other hand, we are in good agreement with the values of a_1 found by Rhodes et al (1990) for $l = 3, 4$ and 5 (426 ± 28 nHz, 412 ± 10 nHz, 406 ± 8 nHz, respectively). It must be pointed out that the agreement with Rhodes et al (1990) may be even better as the autocorrelation method, that they used, systematically overestimates the splittings below $l = 10$ (Brown and Morrow, 1987).

The splitting we found for $l = 2$ confirm the findings of Elsworth et al (1994), Fossat et al (1994), Jiménez et al (1994), and of Toutain and Kosovichev (1994) about a core not rotating much faster than the solar surface.

The measurements made by the LOI are an improvement for low-l p-mode analysis, because the various m components of the modes can be individually detected.

Table 1. LOI frequencies and 1-σ error in (μHz) of low-l p modes (d: modes detected but no frequency estimate available)

n	l=1	l=2	l=3
15	-	-	2407.68 ± 0.15
16	-	2486.06 ± 0.13	2542.00 ± 0.15
17	-	2619.69 ± 0.16	2676.35 ± 0.20
18	d	2754.38 ± 0.10	2811.50 ± 0.18
19	d	2889.74 ± 0.10	2946.80 ± 0.16
20	-	3024.96 ± 0.11	3082.16 ± 0.11
21	3097.71 ± 0.31	3159.67 ± 0.17	3217.84 ± 0.11
22	3233.08 ± 0.15	3295.41 ± 0.18	3353.83 ± 0.45
23	-	3430.89 ± 0.18	3490.05 ± 0.30
n	l=4	l=5	l=6
15	2458.70 ± 0.23	2506.02 ± 0.18	-
16	2592.87 ± 0.17	2641.30 ± 0.21	d
17	2728.80 ± 0.21	2777.20 ± 0.14	d
18	2864.09 ± 0.08	2913.56 ± 0.15	d
19	3000.21 ± 0.14	3049.78 ± 0.12	d
20	3135.89 ± 0.13	3186.23 ± 0.15	d
21	3271.61 ± 0.16	3322.96 ± 0.31	-
22	3407.98 ± 0.24	3460.42 ± 0.32	-
23	3544.12 ± 0.29	-	-

Table 2. LOI sidereal a_1 component of the splitting (in nHz) for low-l p modes. The errors are 1-σ values

n	l=2	l=3	l=4	l=5
15	-	445 ± 46	455 ± 92	438 ± 39
16	457 ± 110	319 ± 59	243 ± 79	405 ± 51
17	525 ± 101	450 ± 74	322 ± 80	409 ± 39
18	362 ± 65	281 ± 73	408 ± 23	418 ± 40
19	258 ± 74	476 ± 59	319 ± 39	430 ± 32
20	301 ± 65	317 ± 52	331 ± 33	408 ± 34
21	497 ± 109	387 ± 50	480 ± 53	405 ± 103
22	807 ± 116	613 ± 215	425 ± 81	132 ± 102
23	484 ± 127	527 ± 140	198 ± 97	-
<>	402 ± 31	392 ± 21	373 ± 14	413 ± 15

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