ANALYSIS OF VARIABILITY OF P-MODE PARAMETERS IN 11 YEARS OF IRIS DATA

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ABSTRACT

11 years of IRIS (the low degree helioseismology network) have been analysed for the study of p-modes parameters variability. The duty cycle of the network data has been improved by the partial gap filling method named “repetitive music”. This paper discusses the variations of all p-modes parameters along these 11 years.

Key words: Sun: oscillations, low degree p-modes, solar activity, data analysis.

1. INTRODUCTION

The IRIS (International Research of Interior of the Sun) network for full disk helioseismology has been operated since July, 1989. The observations consist of daily measurements of the solar radial velocity obtained with a resonant sodium cell spectrophotometer. In this analysis, we have used the IRIS++ data bank (Gelly et al., 1998) (IRIS++ = IRIS + Mark I + LOWL + Cacciani’s MOF). We have access to low-degree p-modes with l ≤ 3. In this work, we use data covering the complete range of solar activity from mid 1989, just before the maximum of the cycle 22 to the end of 1999, just before the next maximum. We have studied p-modes parameters during 11 years, and we report here their dependance with solar cycle and with frequency. The high frequency range (up to the acoustic cutoff frequency 5.5 mHz) has been given special attention. This region of the spectrum is a source of information on the outer layers of the Sun and the origin of solar oscillations.

2. DATA ANALYSIS

We focus on 2 different frequencies parts. First, we calculate annual spectra in the range 1.7 mHz < ν < 3.7 mHz with 4 months timeseries (with 2 months overlapping). Second, we calculate spectra for frequency ν > 3.7 mHz, with 8 days timeseries and 4 days overlapping. To study this frequency range, we take short samples of some days, because in this frequency range p-modes vary quickly and are not very stable. These p-modes have a lifetime of some hours. The IRIS duty cycle is 50-80% during the 4 month summer (June, July, August and September). To increase the duty cycle, we use the technique of the repetitive music, a method of partial gap filling (Fossat et al, 1999). We obtain duty cycles of 80-97% in 4 month summer (Figure 1), (Table 1).

<table>
<thead>
<tr>
<th>Years</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
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<tr>
<td>1989</td>
<td>34.0</td>
<td>53.0</td>
<td>58.0</td>
<td>80.0</td>
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<td>1990</td>
<td>36.6</td>
<td>54.5</td>
<td>63.6</td>
<td>86.0</td>
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<td>59.4</td>
<td>72.8</td>
<td>89.3</td>
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<td>60.3</td>
<td>73.1</td>
<td>89.0</td>
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<td>1993</td>
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<td>50.2</td>
<td>68.7</td>
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<td>59.8</td>
<td>80.6</td>
<td>82.4</td>
<td>97.0</td>
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<tr>
<td>1995</td>
<td>64.4</td>
<td>80.5</td>
<td>89.4</td>
<td>96.9</td>
</tr>
<tr>
<td>1996</td>
<td>59.3</td>
<td>72.2</td>
<td>85.0</td>
<td>93.6</td>
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<td>1997</td>
<td>64.7</td>
<td>79.8</td>
<td>89.7</td>
<td>97.5</td>
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<td>1998</td>
<td>61.5</td>
<td>75.1</td>
<td>88.0</td>
<td>95.9</td>
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<tr>
<td>1999</td>
<td>45.6</td>
<td>63.2</td>
<td>65.9</td>
<td>85.7</td>
</tr>
</tbody>
</table>

Table 1. Duty Cycles (%). (a) annual IRIS++; (b) 4-month summer IRIS++; (c) annual partial gap filled IRIS++; (d) 4-month summer partial gap filled IRIS++

We use 2 methods. The first method is to fit a simple lorentzian model of solar eigenmode as a damped one-dimensional oscillator.

\[ L = \frac{A}{1 + \left(\frac{2\Gamma}{\nu - \nu_0}\right)^2} + B \]  

(1)

with A, amplitude, 2\(\Gamma\), width, \(\nu\) frequency and B, background noise. The p-modes parameters are then extracted by means of a standard maximum likelihood fitting technique. A special fit adapted for gap filling - repetitive music method - is used (Fiery-Fraillon & Appourchaux, 2001), and give results without bias.

In the second method, we calculate the position of the cross-correlation main peak for each spectrum and the reference spectrum (Pallé et al., 1989). Our reference (the same for the 2 methods) is calculated over 2 years 1995 and 1996 - minimum of cycle 22.

3. FREQUENCY SHIFTS

We can see 3 different parts on figure 2:

- below 2.5 mHz, the frequency shift is close to zero: in this frequency range, frequencies do not seem to be sensitive to solar activity.

- between 2.5 and 3.7 mHz, we have the well already observed frequency shift (Anguera Gubau et al., 1992), (Libbrecht & Woodard, 1990), (Jiménez-Reyes et al., 2001), (Howe et al., 1999), (Chaplin et al., 1998). Shift increases with frequency following the famous inverse mode mass law.

- above 3.7 mHz, the frequency shift suddenly drops to zero, and becomes negative after 4.5 mHz up to the 5.5 mHz cutoff frequency (only

4. LINEWIDTHS

With IRIS data, we can have good measurements of p-modes linewidths and amplitudes, and confirm results of others authors (Komm et al., 2000), (Jiménez-Reyes et al., 2001). The linewidths increase with frequency with a plateau of value \(~1\mu Hz\) between 2 and 3 mHz, that becomes a slight dip in the time of small activity near 3 mHz. Above 3 mHz, the linewidths increase and become quickly large. It is visible that the quality of resonance of p-modes increases when the Sun is not spotted and is more "purely spherical" (Figure 3). On the other hand, the amplitudes are changing with opposite phase, being smaller when the Sun is active.
The ratio $\Omega = \frac{r_{\text{Maximum}}}{r_{\text{Minimum}}}$ shows the linewidths variations during the solar cycle. Up to 2.5 mHz, the linewidths are similar. Between 2.5 and 3 mHz, the ratio increases with a maximum at 3 mHz and then decreases (Figure 4). We clearly see that linewidths are larger during maximum, and the effect is more important where the signal is important (around 3 mHz).

![Figure 4. Linewidths Ratio $\Omega$](image)

5. SOLAR CYCLE

The figure 5 shows the p-mode frequencies and their linewidths as a function of time with a one-year resolution, following the solar activity cycle that is also shown for comparison (see the legend). We can see the good correlation between sunspot number and frequency shift in the range 2.6-3.7 mHz (shown as measured by the two mentioned methods), with the linewidth (linewidths are larger during maximum activity: the solar oscillations, because a more important activity, are more damped), and the negative correlation with the high frequencies ($\nu > 3.7 mHz$) shifts.

![Figure 5. p-modes and Solar Cycle. The 3 curves in phase with the sunspot index are the frequency shifts (range 2.6-3.7 mHz) measured by 2 different methods and the linewidth. The curve showing opposite phase is the high frequency shift. (The units are arbitrary)](image)

We have calculated correlations coefficients between frequency shifts and several solar activity indexes. The ones used are the following: $R_1$, the International Sunspot Number; $F_{10}$, the integrated radio flux at 10.7 cm; KPMI, the Kitt Peak Magnetic Index (Harvey, 1984); MPSI, the Mount Wilson Magnetic Plage Strength Index (Ulrich, 1991); TSI, Total Solar Irradiance (Frohlich & Lean, 1998); and the equivalent width of HeI 10830Å averaged over the whole solar disk.

We perform a linear least-squares fit of the type $\Delta \nu = a + b \nu$, where $\Delta \nu$ is the frequency shift observed, $\nu$ represents the activity indexes, and $a$ and $b$ are the intercept and the slope, respectively. On the Figure 7, we can see the good correlation between $F_{10}$ and the frequency shifts. We have also calculated the parametric Pearson correlation coefficient $r_p$, which is a measurement of the strength of the linear relationship between two indexes, and the non-parametric Spearman rank correlation coeffi-

![Figure 6. $IRIS^{++}$ frequency shifts and 10.7cm integrated radio flux as a solar activity index](image)

6. DISCUSSION

The good quality of the IRIS data allows to have good measurements of the variability of p-modes over 11 years - one solar cycle. With IRIS data, we can see the well known increase of frequency shift in the range 2-3.7 mHz, following the mode mass law. We confirm the linewidth increase and the amplitude decrease with activity. During maximum solar activity, oscillations damping is more important than during minimum, so linewidths are larger and amplitudes weaker. Above 3.7 mHz, we observe
Table 2. Correlation coefficients and slope b (in nHz per activity index)

<table>
<thead>
<tr>
<th>Activity Index</th>
<th>r_p</th>
<th>r_s</th>
<th>Slope b</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.98</td>
<td>0.93</td>
<td>2.67</td>
</tr>
<tr>
<td>F10</td>
<td>0.98</td>
<td>0.90</td>
<td>2.77</td>
</tr>
<tr>
<td>KPMI</td>
<td>0.95</td>
<td>0.91</td>
<td>23.2</td>
</tr>
<tr>
<td>MPSI</td>
<td>0.98</td>
<td>0.86</td>
<td>149.1</td>
</tr>
<tr>
<td>TSI</td>
<td>0.91</td>
<td>0.90</td>
<td>406.6</td>
</tr>
<tr>
<td>He</td>
<td>0.98</td>
<td>0.93</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Figure 7. Linear correlation between the frequency shift and the radio flux

A downturn of the frequency shift, which becomes negative above 4.5 mHz with a rapid decrease up to the 5.5 mHz cutoff frequency. This drop was only observed for the moment for the intermediate degree (Ronan et al., 1994), (Jeffries, 1998). The strong increase in the frequency shift with frequency up to 3.7 mHz reflects solar cycle changes and just below the photosphere. The abrupt decline above 3.7 mHz may be the effect of changes in the chromosphere, which acts as a cavity in which p-modes are trapped (Goldreich et al., 1991). For Jain & Roberts (1996), the observed frequency shifts are to be understood as a consequence of both magnetic changes and thermal changes, the rise phase being a consequence of an increase in the mean photospheric magnetic field with the observed abrupt decline following from a combination of an increase in mean chromospheric magnetic field strength and an increase in chromospheric temperature. Although these simultaneous changes explain qualitatively the observed frequency shifts, the required temperature changes are quite large.

It is interesting to know the behaviour of low-degree p-modes frequency shifts above the 5.5 mHz cutoff frequency, in the pseudo-modes range. Jeffries (1998) and Ronan et al. (1994) have shown an upturn above 3.5 mHz for intermediate degrees. The physical origin of the high frequency peaks is not entirely resolved. Kumar & Lu (1991) have described a model in which the spectrum at high frequency is a continuous acoustic spectrum (because these waves are not confined in a cavity) in which high-frequency interference peaks (HIPs) appear due to constructive interference between travelling acoustic waves. Balmforth & Gough (1996) explain “mode-like” structure at high-frequencies by wave reflection which take place at near discontinuities in the density gradient. Wave reflection from the chromosphere-corona transition region results in an “extended” acoustic cavity. Recent time-distance measurements of the high-frequency waves (Jeffries et al., 1997) suggest that a small amount of wave reflection (~ 6%) may be occurring in the Sun’s chromosphere. We are also studying short-time correlations between frequency shift and solar activity indexes.

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