Line Asymmetry of VIRGO and MDI low-degree p modes

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ABSTRACT

Using two time series of 610 days, one of velocity (MDI, LOI-proxy) and one of intensity (VIRGO, SPM) we show that the Lorentzian profile as a model of low-degree p-mode line leads to systematic differences in the determination of mode frequencies for intensity and velocity observations. These differences, as large as 0.1 μHz appear both for degrees l=0,1 and 2. The use of a physics-based asymmetrical line shape to fit the same data has allowed us to significantly reduce these differences in the frequency determination. It turns out that p-mode lines in velocity exhibit a significant negative asymmetry (excess of power in the left wing) whereas p-modes lines in intensity have a positive asymmetry (excess of power in the right wing). The magnitude and sign of asymmetry are directly related to the location of the source of p-mode excitation and to the correlation between mode and solar noise. We show that the results of inversion of the solar core structure are sensitive to the line profile used for the frequency determination.

Key words: p-modes; asymmetry.

1. INTRODUCTION

Duvall et al. (1993), using medium-l spectra averaged over the azimuthal order (m), were the first to show evidence of a line asymmetry in solar p modes. Moreover this asymmetry showed up with opposite sign for intensity and velocity observations. A first attempt was made by Toutain (1993) to detect asymmetry in the low-degree p modes, using the IPHIR data (Fröhlich et al., 1988). A systematic positive asymmetry was measured, but the duration of the observation and the signal-to-noise ratio prevented to conclude that the asymmetry was statistically significant. With SOHO we have access to helioseismic data of long duration and high quality both in velocity (MDI, GOLF) and intensity (VIRGO). In this paper we use MDI (Scherrer et al., 1995) and VIRGO (Fröhlich et al., 1995) time series of 610 days to show that low-degree p-modes exhibit also a significant asymmetry which is of opposite sign for intensity and velocity. Since Woodard (1984) line fitting of low-degree p-modes is done assuming a Lorentzian shape and a chi-square statistics with two degrees of freedom. This is the model of a stochastically excited oscillator. It is therefore necessary to replace this model with a new one which takes into account the asymmetry. Here below we discuss the physically-based model we used to fit the p-mode line. We show how large is the asymmetry on the data we analysed and its effect on the frequency determination. Finally we demonstrate the importance of using corrected frequencies to infer the physical properties of the solar core.

2. THE NEW MODEL OF P-MODE LINE

In their paper Duvall et al. (1993) explained the asymmetry as the consequence of the interaction between an outward-directed wave from the excitation source and a corresponding inward-directed wave passing through the region of wave propagation. Nevertheless this model cannot account for the reversal of asymmetry as observed in intensity and velocity spectra. Nigam et al. (1998), show that this effect can be explained if correlated noise is added to the mode amplitude. In this paper we use the following formula for a potential well model as given by Nigam and Kosovichev (1998)

$$P(x) = A\frac{(1+Bx)^2+B^2}{1+x^2}+n \qquad (1)$$

where $x = 2(\nu-\nu_0)/\Gamma$. In the above formula the fit parameters are A, Γ, ν_0, B, n, the mode amplitude, linewidth, central frequency, the asymmetry coefficient and the uncorrelated background noise, respectively. For B=0 this formula is equivalent to the usual Lorentzian profile. B is the parameter which defines the asymmetry. It is positive for positive asymmetry (excess of power in the right wing of a p-mode line) and negative for a negative asymmetry

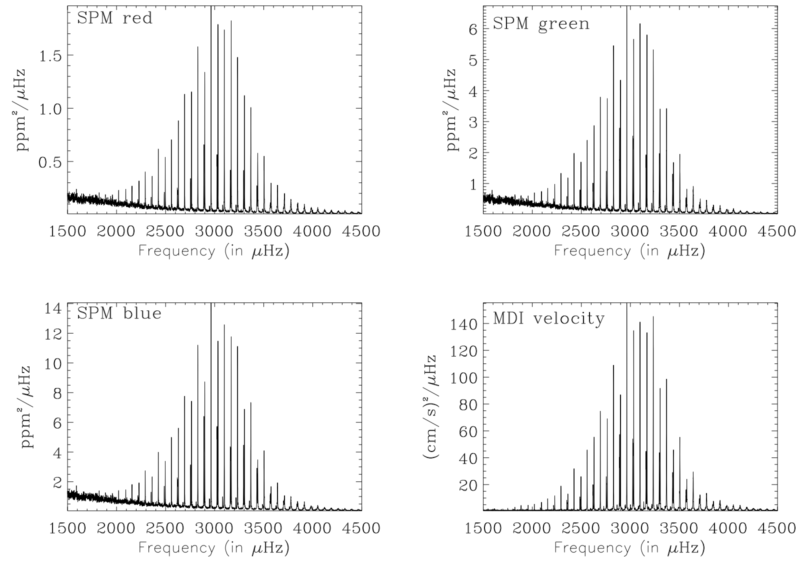

Figure 1. Integrated power spectra for VIRGO/SPM data and MDI velocity. Spectra are smoothed using a 1 μHz running mean.

(excess of power in the left wing of a p-mode line). B*100 is approximately the percentage of line asymmetry according to the definition of Abrams and Kumar (1996). From a physical point of view, there are two factors wich are responsible of the asymmetry : the correlated noise and the source of excitation, see Nigam et al.(1998) for more details.

3. DATASETS AND FITTING TECHNIQUE

For this work we have gathered two time series of 610 days (from 1 May 1996 to 31 December 1997) one from VIRGO the other one from MDI. For VIRGO we have in fact used the three intensity time series of the SPM instrument. In order to use similar datasets the 180-bin MDI velocity data are summed-up to get an equivalent Sun-as-a-star signal. Time series are Fourier transformed to get the usual p-mode power spectra (see Fig.1). As expected the granulation noise affects strongly the intensity data preventing us to analyse lines below 2 mHz. Above 3.5 mHz l=0 and l=2 lines sufficiently overlap to mask a possible effect of the asymmetry. We have therefore worked on a frequency range spanning from 2 to 3.5 mHz only. P-mode lines are fitted using the maximum-likelihood technique with a line profile given by Eq.1 with a constant background noise. We have also fitted lines using a Lorentzian profile in order to compare the frequency determination of both fits. Note that as usually we fit l=0-2 doublet together, assuming a same linewidth and asymmetry, and not separately because they are close to each other in the Fourier domain.

4. ASYMMETRY

Figures 2 and 3 show the parameter B of Eq.1 as a function of mode frequency and degree for SPM data and velocity data, respectively. As expected, the asymmetry has a different sign for velocity and intensity. Nevertheless the frequency-dependence is the same: there is a minimum around 3 mHz. The asymmetry for velocity line seems to be smaller than for intensity. The physical model as described by Nigam et al. (1998) can easily explain the features we described. For a given correlation with noise, B should be proportional to the inverse of the square root of the signal-to-noise ratio. Thus B should be the smallest around 3 mHz and it should increase both towards higher and lower frequencies and because velocity leads to a better signal-to-noise ratio it should also give the smallest asymmetry. This effect also explain why lines of the RED spectrum are slightly more asymmetrical than those of the GREEN and BLUE spectra. This because lines in the RED spectrum have a signal-to-noise ratio which is about 10% smaller than lines in the GREEN and BLUE spectra. It is also interesting to note that Toutain (1993) found with the GREEN and RED channels of the IPHIR instrument similar results for the asymmetry though not significant from a statistical point of view. The formula used for fitting the IPHIR lines was not the one given by Eq.1, but we can convert the asymmetry coefficient α used in the IPHIR paper to the B coefficient as used in this paper. It turns out that IPHIR lines exhibit an asymmetry which is about twice the asymmetry measured in the SPM data. Nevertheless, IPHIR p-modes have a signal-to-noise ratio approximately 4 times poorer than the one of the SPM/VIRGO spectra. If the noise in the p-mode range of the IPHIR spectra has a solar origin and not an instrumental one then the effect of correlated noise as described by Nigam et al. (1998) can therefore explain the factor of 2 between the asymmetry measured in IPHIR and in the SPM spectra. Nevertheless to confirm this explanation we have to show that the granulation noise in the 5-minute range strongly increases as we approach the solar maximum and up to now (May 1998) there is no evidence of such an increase.

5. FREQUENCY DIFFERENCES

Fitting an asymmetrical p-mode line using Eq.1 or a Lorentzian profile will not lead to a same determination of the mode frequency. There is a systematic shift between the two determinations which is a function of B. If B is positive the Lorentzian fit gives a mode frequency which overestimates the intrinsic frequency of the mode. If B is negative the frequency is underestimated. Of course because of the stochastic excitation of the p modes it can happen that it is the other way around for some modes. This is especially likely for modes with narrow linewidths, because the number of bins contributing to the line profile and therefore to the asymmetry is small. These modes have also a poorer signal-to-noise ratio which on one hand enhances the asymmetry because of the correlation but on the other hand tends to mask it.
According to the fact that velocity and intensity have negative and positive asymmetries, respectively, we expect that Lorentzian fits should lead to discrepancies for mode frequency determination using velocity and intensity data. These discrepancies were already mentioned for low-degree p modes by Toutain et al.(1997) and Appourchaux et al.(1997). An analysis of 4-month spectra of the SPM/VIRGO, LOI/VIRGO, MDI-velocity, MDI-intensity and GOLF data has shown that the mode frequencies for intensity lines are in average larger than the velocity lines by about 0.1 μHz. We have done the same analysis with longer SPM and MDI time series (610 days) and we confirm the frequency shift between velocity and intensity. Fig.4 shows the differences between frequency in SPM and MDI as a function of the mode frequency and the degree. The Legend gives the mean value and the variance of the differences for each degree. Though having a large dispersion, as large as the mean value, the differences exhibit a systematic positive shift which can be seen as statistically significant. We can also note that the differences between MDI and RED are significantly larger than those between MDI and GREEN. Therefore there is also a frequency difference thought smaller between RED and GREEN due to the fact that the corresponding spectra exhibit slightly different signal-to-noise ratio as explained in the previous section. If we use the profile as given by Eq.1 instead of a Lorentzian profile to fit the same data we can test its goodness to describe the observations. If this model is better than the Lorentzian one we could expect a clear diminution of the shift between mode frequency determination. Figures 6 and 7 show the shifts we obtained using Eq.1. Taking into account the asymmetry reduces significantly the differences. The likelihood ratio-test (Appourchaux et al., 1995) confirms that the asymmetry is a highly significant parameter. Eq.1 is therefore a good model for describing p-mode line shape.

Table 1. Mean frequency differencies (in μHz) between the intensity (SPM) and velocity (MDI) data.

l	$\overline{\nu_{\rm SPM} - \nu_{\rm MDI}}$(sym.)	$\overline{\nu_{\rm SPM} - \nu_{\rm MDI}}$(asym.)
0	0.151±0.044	0.029±0.066
1	0.136±0.116	0.002±0.143
2	0.056±0.084	0.002±0.122

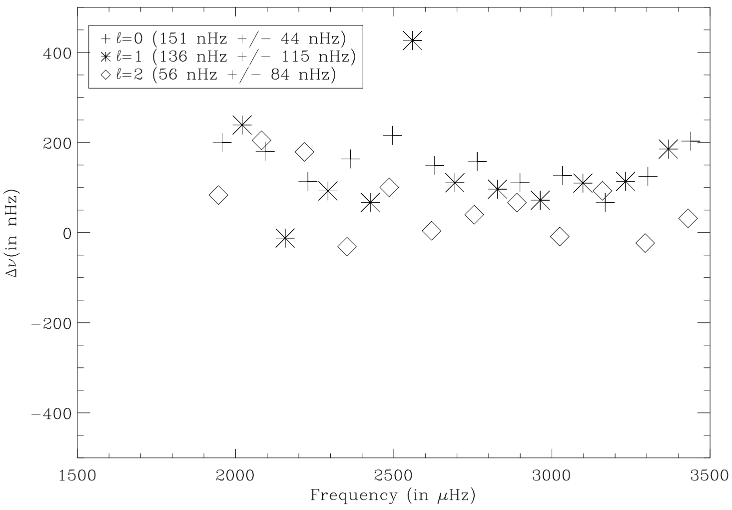

Figure 4. Frequency differences between SPM-RED and MDI frequencies for a Lorentzian profile.

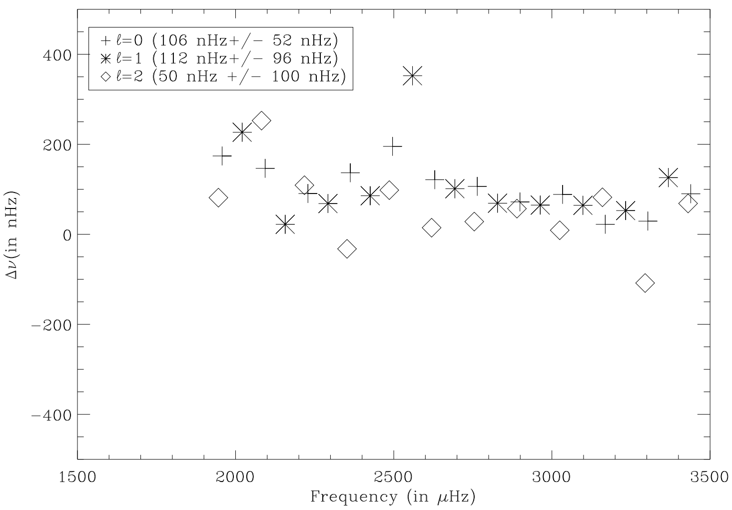

Figure 5. Frequency differences between SPM-GREEN and MDI frequencies for a Lorentzian profile.

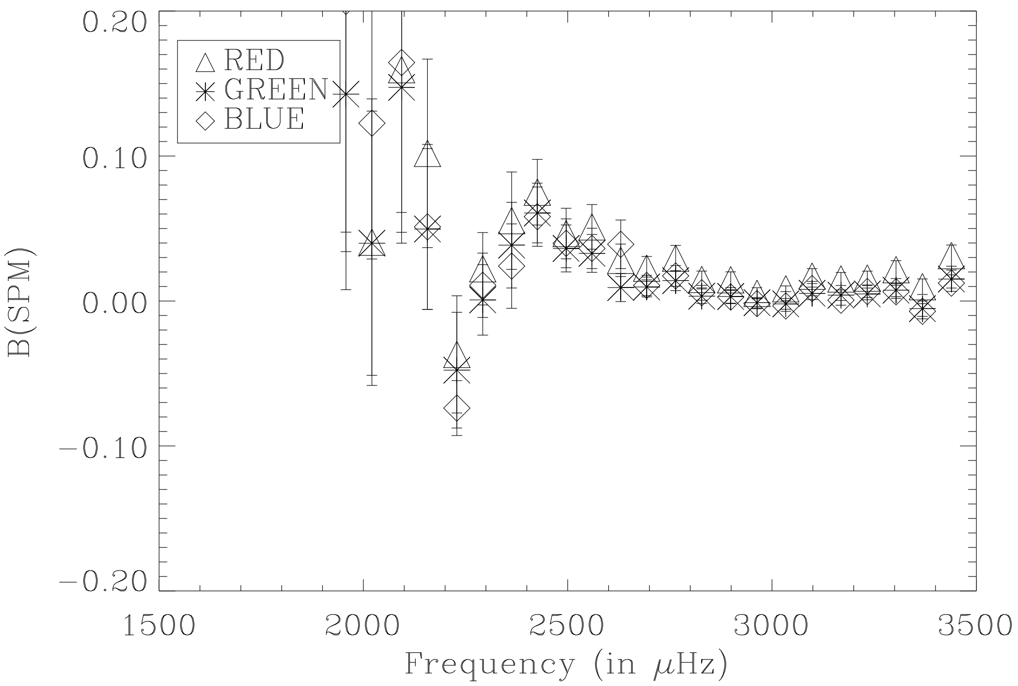

Figure 2. Asymmetry parameter B as a function of mode frequency and degree for SPM/VIRGO.

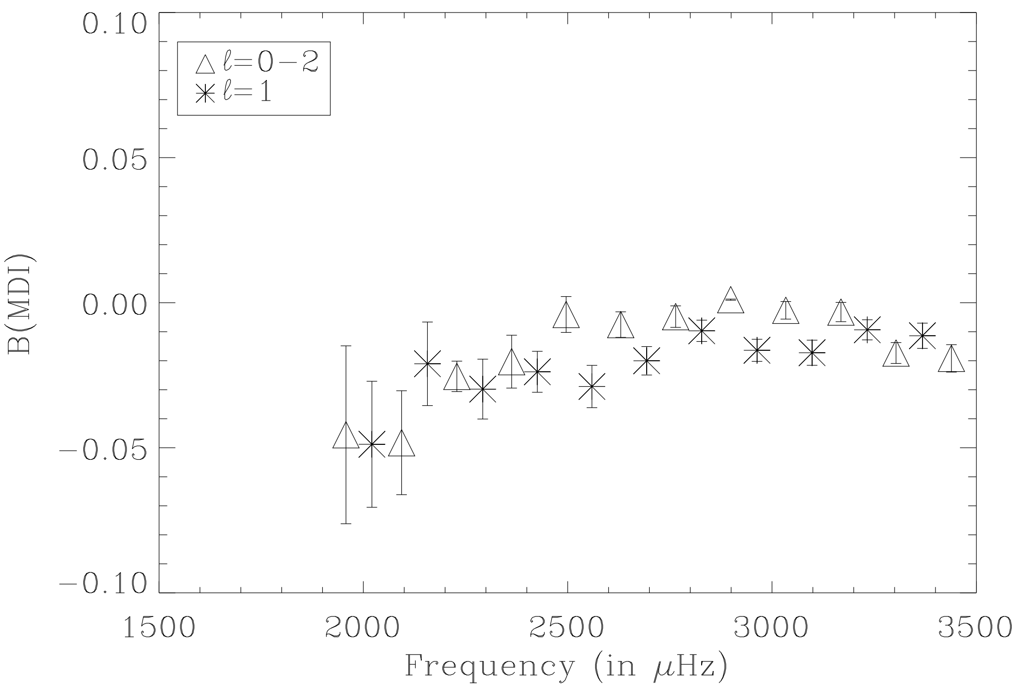

Figure 3. Asymmetry parameter B as a function of mode frequency and degree for MDI velocity.

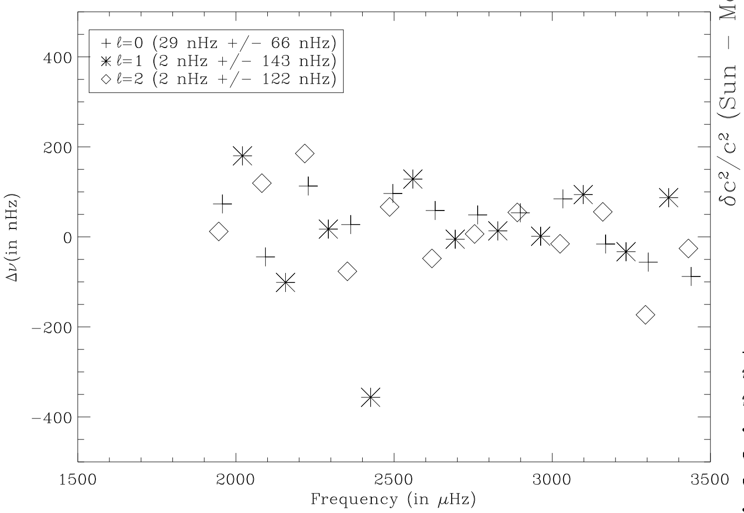

Figure 6. Frequency differences between SPM-RED and MDI frequencies for the profile of Eq.1.

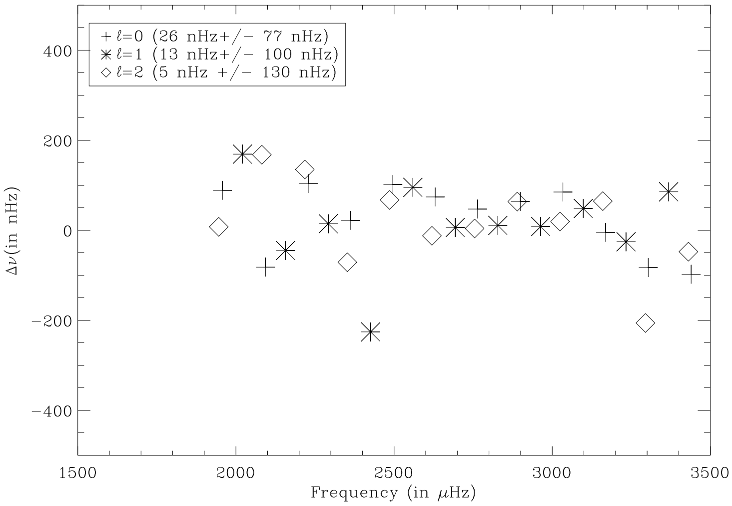

Figure 7. Frequency differences between SPM-GREEN and MDI frequencies for the profile of Eq.1.

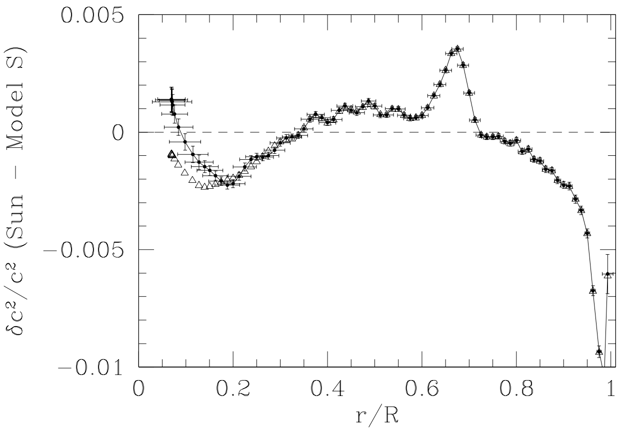

Figure 8. Differences between the squared sound speed inferred from the frequencies of $l = 0-2$ modes and medium-l frequencies of Rhodes et al.(1997) and the squared sound speed of solar model S. The solid curve and the triangles are obtained with low-degree mode frequencies corrected and not corrected from asymmetry, respectively. The vertical error bars show the formal error estimates, and the horizontal bars show the characteristic width of the localized averages.

6. IMPLICATIONS FOR THE SOLAR CORE STRUCTURE

It is important to examine the implications of these frequency shifts on the inversion of the solar core structure . For this, we have combined MDI l=0,1,2 frequencies corrected from asymmetry with a set of frequencies for l=3-300 obtained by Rhodes et al. (1997) from the MDI medium-l data (not corrected for asymmetry). The solar structure was inferred using a version of the optimally localized averaging inversion method of Gough and Kosovichev (1988). Figure 8 shows the relative difference between the square of the sound speed in the Sun and the sound speed of the standard model of Christensen-Dalsgaard et al. (1996). The effect of the asymmetry of p-mode lines appears through the difference between the solid line (using profile of Eq.1) and the triangles (using a Lorentzian profile). Though small, between 0.1 and 0.2 %, the effect of the asymmetry is significant. The clear change of slope at 0.2 R can be the signature of an effect taking place below this boundary, for example a partial mixing in the core (Gough and Kosovichev, 1988). Fröhlich et al, 1997 have also pointed out the possible effect on inversion of systematic differences between LOI and LOWL frequencies.

7. CONCLUSIONS

Using a SPM/VIRGO intensity time series and a MDI velocity time series of 610 days, we have shown that if a Lorentzian profile is used to fit the low-degree p-mode lines, then intensity and velocity observations lead to systematic differences in the determination of the mode frequencies, differences as large as 0.1 μHz. This result confirms the work of Toutain et al. (1997) done in the frame of inter-comparison between the SOHO helioseismology experiments. We have tested the hypothesis put forward to explain these discrepancies, that is to say p-mode lines are slightly asymmetric and the asymmetry is not the same for velocity and intensity measurements. In this paper we show that low-degree p-modes exhibit the same signed asymmetry as the one found by Duvall et al. (1993) for medium-l p modes. Velocity lines have a negative asymmetry whereas intensity lines have a positive asymmetry. Nigam et al. (1998) explain this fact and provide a model of asymmetric line profile. Using this model we have shown that we can significantly reduce the frequency differences between intensity and velocity frequencies. Moreover correcting the low-degree p-mode frequencies from asymmetry slightly but significantly modifies the results of inversion of the solar core structure. It is therefore likely that our understanding of the solar structure will benefit from taking into account the asymmetry of p-mode lines.

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