Asymmetry and frequencies of low-degree p-modes and the structure of the Sun's core

T. Toutain[1], T. Appourchaux[2], C. Fröhlich[3], A.G. Kosovichev[4], R. Nigam[4], and P.H. Scherrer[4]

[1]*Département CASSINI, Observatoire de la Côte d'Azur, Nice, France,*

[2]*Space Science Department, European Space Research and Technology Center, 2200 AG Noordwijk, The Netherlands,*

[3]*Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, 7260 Davos-Dorf, Switzerland,*

[4]*W.W.Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085*

ABSTRACT

Accurate determination of frequencies of low-degree solar p modes is an important task of helioseismology. Using 610 days of solar oscillation data observed in Doppler velocity and continuum intensity from two Solar and Heliospheric Observatory (SOHO) instruments: Michelson Doppler Imager (MDI) and SunPhotoMeter (SPM), we show that fitting the spectra with Lorentzian profiles leads to systematic differences between intensity and velocity frequencies as large as 0.1 μHz for angular degrees l=0,1 and 2 due to the opposite asymmetry between intensity and velocity. We use a physics-based asymmetrical line shape to fit p-mode lines and demonstrate that their asymmetry is statistically significant and that frequency differences are considerably reduced. These measurements provide more accurate estimates of the solar eigenfrequencies. We discuss inferences of the structure of the solar core.

Subject headings: methods: data analysis — Sun: interior — Sun: oscillations

1. Introduction

An accurate determination of frequencies of solar acoustic (p) modes of low angular degree l is necessary to infer the structure and rotation of the solar core. Since the work of Duvall et al. (1993) based on oscillation spectra averaged over the azimuthal order, m, the line shape of medium-l p modes have been considered to be possibly asymmetric. Moreover, this asymmetry showed up with opposite sign for modes observed in intensity and in velocity. In standard techniques of measuring solar frequencies (e.g. Anderson et al., 1990) the asymmetry is not taken into account, and the line shape is assumed to be a Lorentzian. This leads to systematic errors in frequency measurements, and thus to errors in helioseismic inferences of the structure of the Sun. Toutain et al. (1997) have observed frequency differences of the order of 0.1 μHz between intensity and velocity low-degree p-mode lines when a symmetric Lorentzian fit was employed. In this *Letter* we show that these frequency differences can significantly be reduced using our model of an asymmetrical line profile.

The first successful attempt to detect the asymmetry of low-l modes was made by Toutain (1993) using the intensity data from the IPHIR space experiment (Fröhlich et al., 1990). However, the IPHIR data being the longest intensity time series available at that time, had a poor resolution and signal-to-noise ratio to make reliable conclusions about the asymmetry and corresponding frequency corrections.

The oscillations of the Sun have been observed continuously for about 2 years with three experiments on board SOHO. Two of these experiments are VIRGO (Fröhlich et al., 1995) which is measuring oscillations of the solar irradiance with a triple sun-photometer (SPM) and a 16-pixel imager (LOI, Appourchaux et al., 1995) and the MDI which is measuring with a CCD detector velocity oscillations in the Ni 6768 line (Scherrer et al., 1995). We have used the longest available time series from both experiments consisting of 610 days of integrated velocity and spectral irradiance (at 400, 500 and 862 nm) to accurately measure the parameters of the p-modes for degrees l=0,1 and 2 in a frequency domain ranging from 2000 to 4000 μHz.

We discuss the fact that the shape of p-mode lines significantly departs from a Lorentzian profile. We use a theoretical model by Nigam & Kosovichev (1998) to fit the asymmetrical shape found in the data. We fit both intensity and velocity lines to determine the frequency dependence of the asymmetry and present new estimates of eigenfrequencies of low-degree modes which are particularly important for determining the structure of the Sun's energy-generating core.

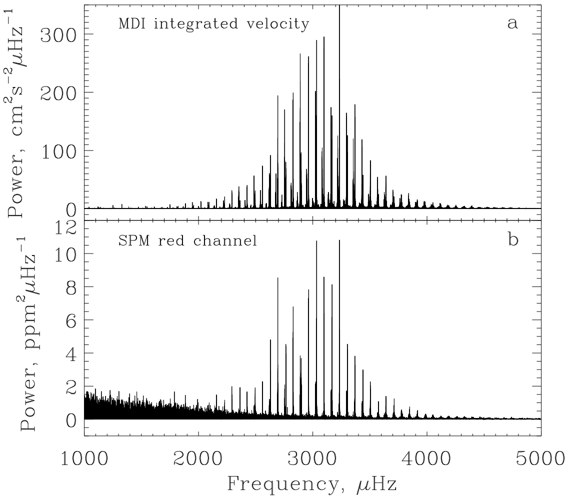

Fig. 1.— Oscillation power spectra of low angular degree solar p modes obtained from 610-day time series of a) MDI integrated velocity, and b) VIRGO/SPM intensity (red channel) measurements.

2. Integrated velocity and intensity power spectra

The power spectra of the 610-day time series are plotted in Fig.1 in a frequency range spanning from 1000 to 5000 μHz. Below 2000 μHz we hardly see p-mode lines in the intensity data because of granulation noise which steeply increases, and above 4000 μHz, mode linewidths are such that modes of degrees 0 and 2 overlap. We therefore restrict ourselves to work in this frequency range to compare the results from the velocity and intensity data. Because of the stochastic nature of solar oscillations, the power in each frequency bin of a line is distributed with a large variance around its expectation value (Woodard, 1984). A smoothing of the line is therefore necessary to reveal its fine structure. Line asymmetry is mainly visible on the edges of the power spectra. As an example, we have plotted in Fig. 2 the l=0, n=12 line both for MDI and SPM (red) spectra. The lines are smoothed with a 1 μHz box-car average in

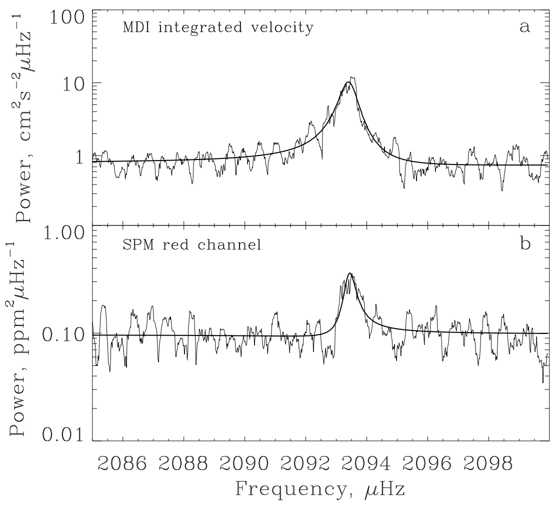

Fig. 2.— Smoothed l=0 n=12 line for MDI (a) and SPM (b) with a box-car average of 1 μHz.

order to enhance the asymmetry of the profiles. On top of the profiles are plotted results of fitting using a model of the asymmetrical line shape as described in the next section. The line asymmetry which is reversed between velocity and intensity power spectra is apparent.

3. Physical model for p-mode line asymmetry and fitting formula

Physically, asymmetry is a result of an interaction between an outward-directed wave from the source and a corresponding inward-directed wave that passes through the region of wave propagation (Duvall et al. 1993). As illustrated in Fig.2, the velocity power spectrum exhibits negative asymmetry (more power on the lower frequency end of the peak) whereas the intensity power spectrum shows positive asymmetry (more power on the higher frequency end of the peak). This reversal of asymmetry can be explained if correlated noise is added to the amplitude spectra (Nigam et al. 1998).

The asymmetry in velocity and intensity power spectra is of opposite sense because a component of the solar noise that is correlated with the source is present in the observed signal. The correlated component of the noise is below a certain threshold to preserve the asymmetry obtained by the model (Nigam et al. 1998) in the velocity power spectrum but that it is large enough (the correlated component is above a certain threshold) to reverse the asymmetry in the intensity spectrum. This is due to the fact that the correlated noise shifts the zero points in the amplitude spectra of the pressure perturbation. The uncorrelated noise plays no role in the reversal of asymmetry because it adds to the power not to the amplitude spectrum.

The solar intensity and velocity oscillations are observed from variations in an absorption (Fraunhofer) line or, as in the case of the SPM, from intensity variations in relatively broad bands of the solar spectrum. These variations consist of two parts: solar oscillation modes and granulation noise. Because the oscillation modes are excited by granulation the granulation signal (noise) is partially correlated with the oscillations. According to Goode et al (1998) the solar oscillations are excited in the intergranular dark lanes. Thus, the observed intensity variations have a noise component which is caused directly by the dark lanes and correlated to the amplitude of the oscillations. Roxburgh and Vorontsov (1997) have suggested that the granulation overshoot forms the correlated component of the noise to the velocity signal. However, the observations show higher level of noise in the intensity data, and support the idea by Nigam et al. (1998) that the line asymmetry in the intensity power spectra is reversed due to the correlated noise in the intensity observations.

To measure the properties of solar oscillations we employed an asymmetric fitting formula of Nigam & Kosovichev (1998) for the power, P:

$$P(x) = \frac{A\left[(1+Bx)^2 + B^2\right]}{1+x^2}, \qquad (1)$$

where $x = 2(\nu - \nu_0)/\gamma$, ν_0 is the mode eigenfrequency, γ is the linewidth, A is the power amplitude, and B is a parameter which controls the asymmetry. This parameter is positive for positive asymmetry and negative for negative asymmetry. It contains the effects of correlated noise and the properties of the excitation source (mainly, its location and type), the two factors that are responsible for asymmetry. To this formula one adds the usual linear background while carrying out the fitting.

4. Line asymmetry

According to the line shape model described in the previous section we have fitted l=0-2 doublets and the

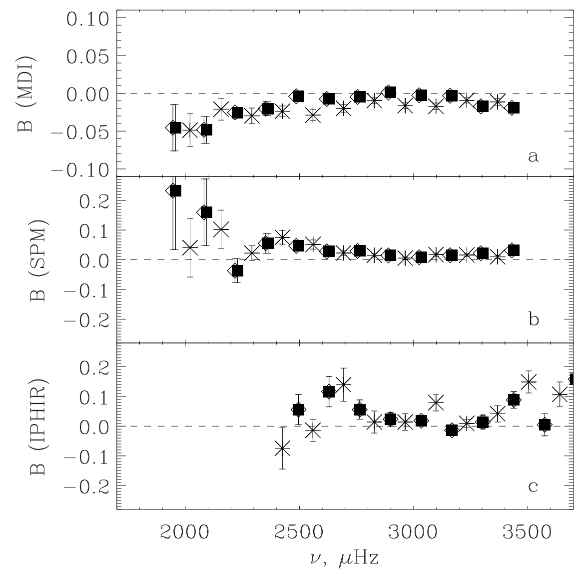

Fig. 3.— Asymmetry coefficient B for l = 0 (squares), l = 1 (crosses) and l = 2 (diamonds) modes as a function of mode frequency for a) MDI, b) SPM data, and c) IPHIR data.

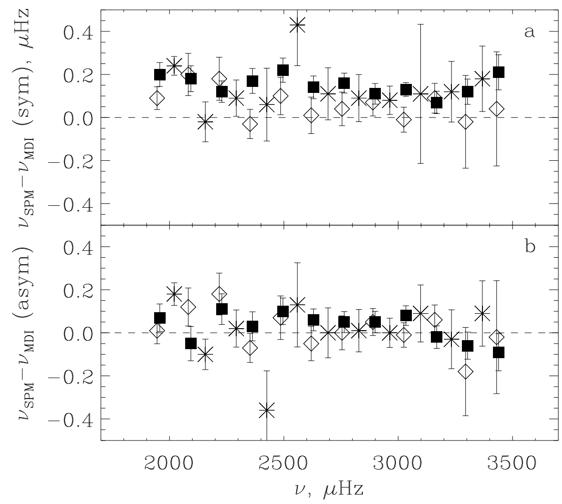

Fig. 4.— Frequency differences between SPM and MDI frequencies for l = 0 (squares), l = 1 (crosses) and l = 2 (diamonds) modes estimated using a) a symmetrical Lorentzian profile, and b) the asymmetrical line profile (Eq. 1). The errorbars are the 1-σ errors.

l=1 lines between 2000 and 4000 μHz. The technique of fitting is a standard maximum likelihood technique. Usually for a disk-averaged spectrum we fit simultaneously the line for l=0 and 2 because they overlap. We therefore give a mean asymmetry for these degrees. The modes of l=1 are fitted assuming 2-component rotationally split multiplets of m=1 and -1, both components having the same asymmetry coefficient. The asymmetry coefficient is plotted in Fig.3 as a function of frequency for the MDI (a) and SPM (b) data. It is clear from these results that, according to the definition of asymmetry we have, velocity lines exhibit negative asymmetry whereas intensity lines exhibit positive asymmetry. Moreover the frequency dependence of the asymmetry is similar in both cases. Asymmetry seems to have a minimum around 3000 μHz and appears to be smaller for the velocity than for the intensity at least for low and high frequencies. Both effects can easily be explained if correlation with noise along with the source exciting the modes is the factor of asymmetry (Nigam et al., 1998). In this case for a given correlation the asymmetry is a function of the square root of the inverse of the signal-to-noise ratio, which is largest around 3000 μHz and which is bigger in general for the velocity spectra compared to the intensity spectra' . These arguments also explain why lines in the red spectrum have slightly larger asymmetries compared to those from the SPM green channel spectrum. This is because the signal-to-noise ratio in the red is about 10% lower than in the green. On the other hand, blue and green signals are very well correlated and have the same signal-to-noise ratios leading to the same asymmetry.

It is interesting to compare these asymmetries with those obtained with IPHIR (Fröhlich et al., 1990), which is an instrument similar to the SPM/VIRGO instrument. IPHIR lines were fitted with an empirical line shape formula (Toutain, 1993) which has the property to describe well the asymmetrical profile shown by Duvall et al.(1993). Compared to SPM, IPHIR data have a signal-to-noise ratio in power which is 3 times smaller. If the noise were to be solar noise and according to our model of noise-source correlation we would expect the asymmetries with IPHIR to be 2 times larger than with SPM, and that is what they are. It is interesting to note that an increase in solar noise for a fixed line amplitude should mask the line asymmetry, but it turns out to be opposite with IPHIR. The asymmetries from the IPHIR data are generally larger than the SPM asymmetries. It is therefore consistent to think that IPHIR noise in the 5-minute range is solar noise and that the p-mode amplitudes are correlated with the noise.

5. Frequency differences

The frequency differences from our symmetrical (Lorentzian) fits to the MDI and SPM red channel data are plotted in Fig.4a. There is a systematic shift both for l=0-2 and l=1 frequencies. The frequencies inferred from the SPM intensity spectrum are systematically higher than the frequencies from the MDI velocity spectrum, as one would expect due to the reversal of line asymmetry. These differences are of the order of 0.1 μHz.

Using the asymmetrical formula given in Eq.(1) we have recomputed the mode frequencies. The results are plotted in Fig.4b. Obviously, the differences are significantly reduced when an asymmetrical profile is used. We have tested the statistical significance of the asymmetry using the likelihood ratio-test (Appourchaux et al, 1995) and find that it is highly significant in most cases. Table 1 shows mean frequency differences between intensity and velocity data obtained with both symmetrical and asymmetrical fits. The close agreement between frequencies from the asymmetrical fits means that these frequencies provide more accurate approximation to the solar mode eigenfrequencies than the frequencies previously measured with a symmetrical Lorentzian profile. In Table 2, we provide a list of the frequencies obtained from the asymmetrical fits to the MDI velocity spectra in the range from 1000 to 4000 μHz.

6. Implications for the solar core structure

To determine the hydrostatic structure of the Sun we combined the frequencies of the low-degree modes with the frequencies of $l = 3-300$ obtained by Rhodes et al (1997) from the MDI medium-l data. The medium-l frequencies which constrain the structure outside the solar core have not been corrected for the asymmetry effect. The spherically symmetric structure of the Sun was determined by using a version of the optimally localized averaging inversion method of Gough & Kosovichev (1988). Figure 5 shows the relative difference between the square of the sound speed in the Sun and the standard solar model of Christensen-Dalsgaard *et al.* (1996). In the central core, the sound speed determined using the frequencies from the asymmetrical fits (solid curve with errorbars) is approximately 0.2-0.3% higher than that inferred from the symmetrical frequency fits. This shift of the sound speed profile does not result in any dramatic changes in our knowledge of the solar core structure. However, it may be important for understanding the difference between the Sun and the standard model.

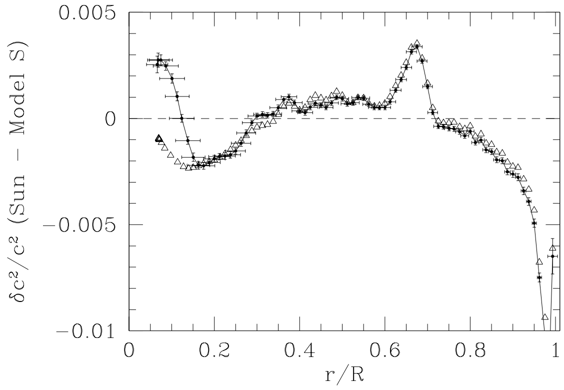

Fig. 5.— The differences in the squared sound speed between the Sun and the solar model S inferred from the frequencies of $l = 0 - 2$ modes and the medium-l frequencies of Rhodes et al. (1997). The solid curve with the crosses shows the results obtained with the asymmetrically fitted low-degree modes; the triangles represent the result of the symmetrical (Lorentzian) fits to the mode lines of the oscillation power spectrum. The vertical error bars show the formal error estimates, and the horizontal bars show the characteristic width of the localized averages.

It has been noted that the sound-speed perturbation profile in the central core is consistent with partial mixing (Gough & Kosovichev, 1988). The change of slope at 0.2 R may indicate the boundary of mixing. Of course, at this stage, other possible explanations, e.g. variations of opacity and nuclear reaction rates, are not ruled out. Also, we note that our inversion results are not fully consistent with the recent results from GOLF (Turck-Chiéze *et al.*, 1997), in which, however, the asymmetry effect was not taken into account.

7. Conclusions

We have studied p-mode frequency differences between velocity and intensity data using 610 days

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

Table 2

Frequencies (in μHz) of low-degree modes obtained with the asymmetrical line profile from the 610-day MDI time series.

n	$l=0$	$l=1$	$l=2$
6		1039.463± 0.014	1104.768± 0.004
7		1185.336± 0.185	1250.563± 0.006
8	1263.187± 0.019	1329.645± 0.004	1394.678± 0.005
9	1407.460± 0.021	1472.827± 0.019	1535.863± 0.017
10	1548.289± 0.019	1612.719± 0.023	1674.549± 0.011
11	1686.578± 0.022	1749.269± 0.015	1810.298± 0.014
12	1822.254± 0.039	1885.107± 0.040	1945.799± 0.016
13	1957.417± 0.040	2020.812± 0.024	2082.139± 0.019
14	2093.478± 0.042	2156.827± 0.026	2217.701± 0.020
15	2228.711± 0.052	2292.018± 0.025	2352.267± 0.020
16	2362.780± 0.060	2425.586± 0.026	2485.934± 0.022
17	2496.113± 0.054	2559.224± 0.029	2619.623± 0.021
18	2629.723± 0.047	2693.424± 0.027	2754.460± 0.020
19	2764.116± 0.046	2828.199± 0.027	2889.560± 0.019
20	2898.955± 0.047	2963.307± 0.025	3024.731± 0.019
21	3033.710± 0.045	3098.188± 0.028	3159.874± 0.040
22	3168.641± 0.053	3233.267± 0.030	3295.048± 0.026
23	3303.425± 0.063	3368.782± 0.040	3430.708± 0.040
24	3439.049± 0.082	3504.431± 0.063	3566.817± 0.057
25	3574.778± 0.129	3641.038± 0.095	3703.365± 0.086
26	3710.645± 0.186	3777.834± 0.187	3840.296± 0.140
27	3848.251± 0.691	3914.816± 0.302	

of MDI integrated velocity and VIRGO/SPM intensity. Fitting l=0-2 p-mode lines with commonly used Lorentzian profiles leads to frequency differences of the order of 0.1 μHz between intensity and velocity and also to a smaller extend between different wavelengths in intensity. Using instead a model of an asymmetrical line profile based on excitation of solar oscillations by a localized source and its correlation with the solar noise in the observed velocity and intensity signals gives frequency differences which are significantly smaller than the differences resulting from Lorentzian fits. The asymmetrical line profile provides more accurate estimates of the eigenfrequencies of solar oscillations. The asymmetry effect results in small (0.1-0.2%) but significant changes in the inferred sound-speed inversion in the energy-generating core, which may be important for understanding the physical processes in the core.

REFERENCES

Anderson, E.R., Duvall, T.L., Jr. & Jefferies, S.M. 1990, ApJ, 364, 699

Appourchaux, T., Telljohann, U., Martin, D., Fleur, J. & Leveque, S. 1995, in Fourth SOHO Workshop Helioseismology. Proceedings. ESA SP-376, eds. J.T. Hoeksema, V. Domingo, B. Fleck & B. Battrick (Paris: ESA) vol.2, 359

Appourchaux, T., Andersen, B.N., Fröhlich, C., Jiménez, A., Telljohan, U., Wehrli, C., 1997, Sol. Phys., 170, 27

Christensen-Dalsgaard, J., Däppen, W., et al. 1996, Science, 272, 1286

Duvall, T.L. Jr., Jefferies, S.M., Harvey, J.W., Osaki, Y., & Pomerantz, M.A. 1993, ApJ, 410, 829

Fröhlich, C., Toutain, T., Bonnet, R.M. et al. 1990, in Inside the Sun, ed. G. Berthomieu & M. Cribier, (Dordrecht: Kluwer), 279

Fröhlich, C., Romero, J., Roth, H. et al. 1995, Sol. Phys., 162, 101

Goode, P.H., Strous, L.H., Rimmele, T.R., Stebbins, R.T. 1998, ApJ, 495, L27

Gough, D.O. & Kosovichev, A.G. 1988, in Seismology of the Sun and Sun-like Stars, ed. E.J.Rolfe, (Paris: ESA), 195

Nigam, R., Kosovichev, A.G., Scherrer, P.H., & Schou, J. 1998, ApJ, 495, L115

Nigam, R. & Kosovichev, A.G. 1998, ApJ, in press.

Rhodes, E.J.,Jr., Kosovichev,A.G., Schou,J, Scherrer,P.H. & Reiter,J. 1997, Sol. Phys., 175,

Roxburgh, I.W. & Vorontsov, S.V. 1997, MNRAS, 292, L33

Scherrer,P.H., Bogart, R.S., Bush, R.I. et al. 1995, Sol. Phys., 162, 129

Toutain, T. 1993, in IRIS VI. Proc. Sixth IRIS Workshop, eds. D.O.Gough & I.W. Roxburgh. (Univer. of Cambridge), 28

Toutain, T., Appourchaux, T., Baudin, F. et al. 1997, Sol. Phys., 175, 311

Turck-Chiéze, S. et al. 1997, Solar Phys., 175, 247

Woodard, M. 1984, Short-Period Oscillations in the Total Solar Irradiance, Ph.D. Thesis, (San Diego: Univ. Calif.)