CHARACTERISTICS OF HIGH DEGREE P-MODES USING RING DIAGRAM ANALYSES

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ABSTRACT

We study the properties of high-degree p-modes using ring diagram analyses. Ring diagrams produced from full-disc Doppler velocity, continuum and line-depth images of the Sun obtained by the Michelson Doppler Imager (MDI) are studied to check how mode characteristics such as asymmetry, line-width etc. vary with the type of observable used for producing the spectra. We have selected data from a low solar activity period to ensure that the activity-related effects do not influence our conclusions.

Key words: Sun: oscillations; Sun: interior.

1. INTRODUCTION

Ring diagram analyses has been used to study large scale flows in outer region of the Sun (Hill 1988; Patron et al. 1997; Basu et al. 1999). This technique involves studying high-degree p-modes from 3d spectra that are obtained from parts of the solar surface which are tracked with an average rotation rate. The peaks in these power spectra are known to be asymmetric (Basu & Antia 1999) and the nature and magnitude of asymmetry depends on type of images used in calculating the spectra. Thus the asymmetry is different in spectra obtained from velocity, intensity or line-depth images. In this work we examine the difference between these types of spectra to check how the asymmetry and other characteristics differ between spectra obtained from different observables.

2. DATA AND TECHNIQUE

We have used data from MDI full-disk images taken during Carrington rotation 1911 and 1912 when the solar activity was near minimum. Each region covers 256 × 256 pixels and is tracked for 1664 minutes. We have used spectra from the equatorial region near the central meridian to minimize projection effects. The continuum spectrum was obtained from observations during 1996 July 21–23, while the line-depth spectrum was obtained from observations during 1996 August 19–20. We have used two velocity spectra, one contemporaneous with the continuum spectrum and the other with the line-depth spectrum. There is very little difference between fits to the two velocity spectra.

To fit the 3d spectra we use the model with asymmetric peak profiles as used by Basu & Antia (1999)

$$P(k_x,k_y,\nu) = \frac{e^{B_1}}{k^3} + \frac{e^{B_2}}{k^4} + \frac{\exp(A_0 + (k-k_0)A_1 + A_2(\frac{k_x}{k})^2 + A_3\frac{k_x k_y}{k^2})S_x}{x^2+1} \quad (1)$$

where

$$x = \frac{\nu - ck^p - U_x k_x - U_y k_y}{w_0 + w_1(k-k_0)}, \quad (2)$$

$$S_x = S^2 + (1+Sx)^2 \quad (3)$$

and $k = k_x^2 + k_y^2$. The 13 parameters $A_0, A_1, A_2, A_3, c, p, U_x, U_y, w_0, w_1, S, B_1$ and B_2 are determined by fitting the spectra using a maximum likelihood approach (Anderson et al. 1990). Here $\exp(A_0)$ is the amplitude of peak, w_0 is the half-width, ck^p is the mean frequency. The parameter S measures the asymmetry in the peak profile. The form of asymmetry is the same as that used by Nigam & Kosovichev (1998). To fit 3d spectra obtained from continuum observations we use a slightly different form where background is represented as $\frac{e^{B_1}}{k} + \frac{e^{B_2}}{k^2}$ and we also set the parameter $w_1 = 0$. The latter change improves the stability of the fits.

In addition to fitting the 3d spectra, we also take azimuthal average for each spectra to obtain 2d spectra in k-ω. These spectra have also been fitted to calculate the mean frequencies and other characteristics of p-modes. For this purpose we use a model (Antia & Basu 1999)

$$P(k,\nu) = \frac{e^{A_0}[(1+Sx)^2 + S^2]}{1+x^2} + e^{b_1}[1 + b_2(1-\nu/\nu_c)], \quad (4)$$

where $x = (\nu - \nu_0)/w_0$ and S is a parameter that controls the asymmetry. The 6 parameters, $A_0, \nu_0, w_0, S, b_1, b_2$ are determined by fitting the spectra.

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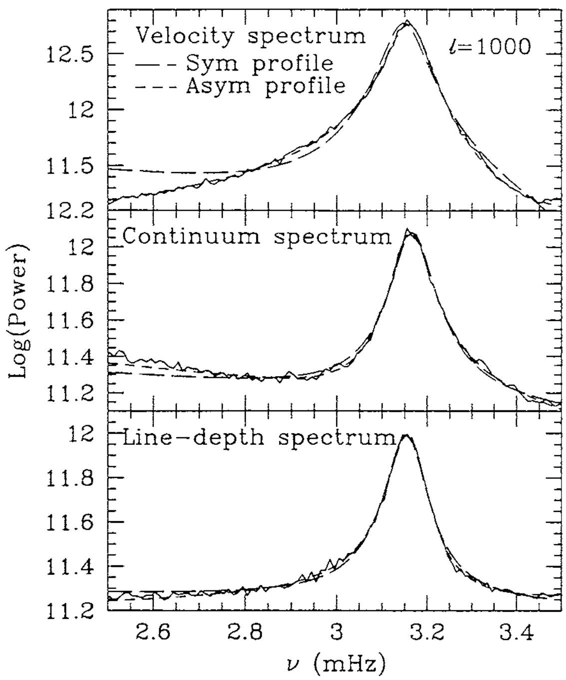

Figure 1. Fits to the $\ell = 1000$ f-mode in various spectra, using symmetric and asymmetric peak profiles.

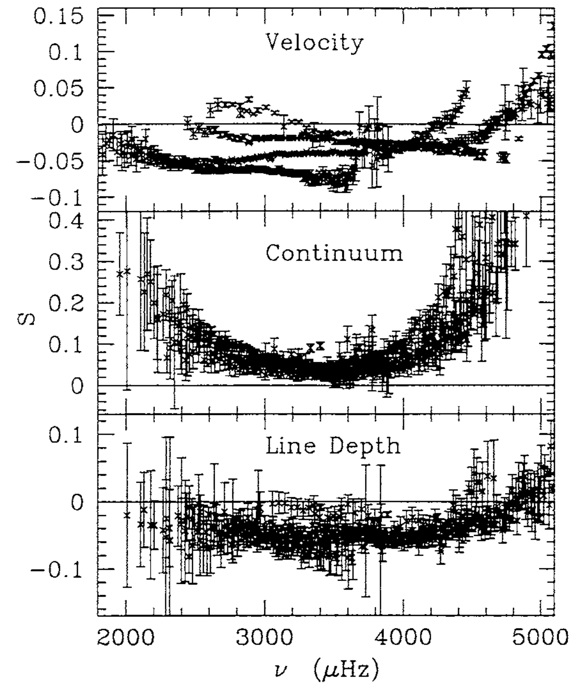

Figure 2. Asymmetry parameter, S obtained from fits to different 2d spectra as labelled in the respective panel.

3. RESULTS

We first consider the fits to azimuthally averaged 2d spectra. Fig. 1, shows typical fits to the spectra obtained from velocity, continuum intensity and line-depth, using both symmetric ($S = 0$) and asymmetric peak profiles. It is clear that the peak in all three spectra are asymmetric, with velocity and line-depth spectra showing negative asymmetry ($S < 0$), i.e., there is more power on lower frequency side. On the other hand, the peaks in intensity spectrum shows positive asymmetry. In all cases, the fit is improved if asymmetry is included in the fitted peak profile. The peak to background ratio is largest for velocity spectrum and hence the asymmetry is seen more clearly in this spectrum. As a result, it is easier to fit the velocity spectrum.

Fig. 2 shows the asymmetry parameter, S, estimated from different spectra. It is clear that this parameter is negative for most modes in velocity and line-depth spectra, while it is positive for most modes in continuum spectra. There is also some variation with frequency and degree. The reversal of sign of asymmetry between velocity and intensity spectra has been attributed to correlation between background and peaks (Nigam et al. 1998).

Since the peaks in the power spectra are asymmetric, the use of symmetric peak profiles for fitting the spectra cause the estimated frequency to be shifted away from the true value of the frequency. Fig. 3 shows the frequency shift between fits using asymmetric and symmetric peak profiles. For velocity and line-depth spectra, the frequency shift is positive while for continuum spectra

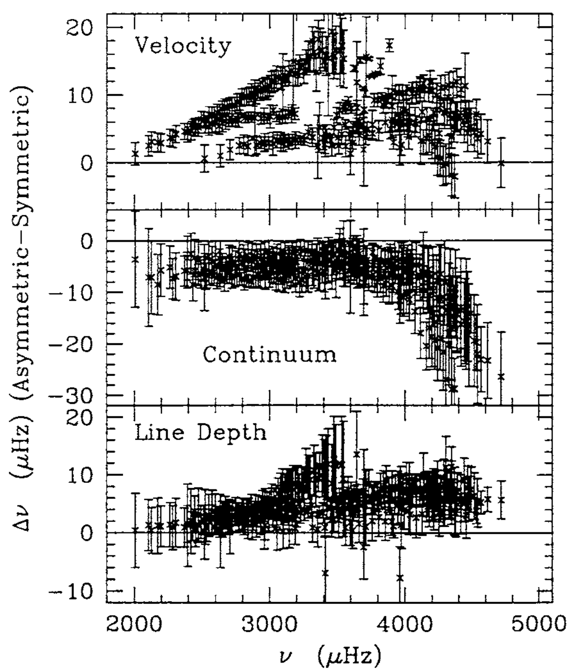

Figure 3. Frequency shift between fits to asymmetric and symmetric profiles for different 2d spectra as labelled in the respective panel.

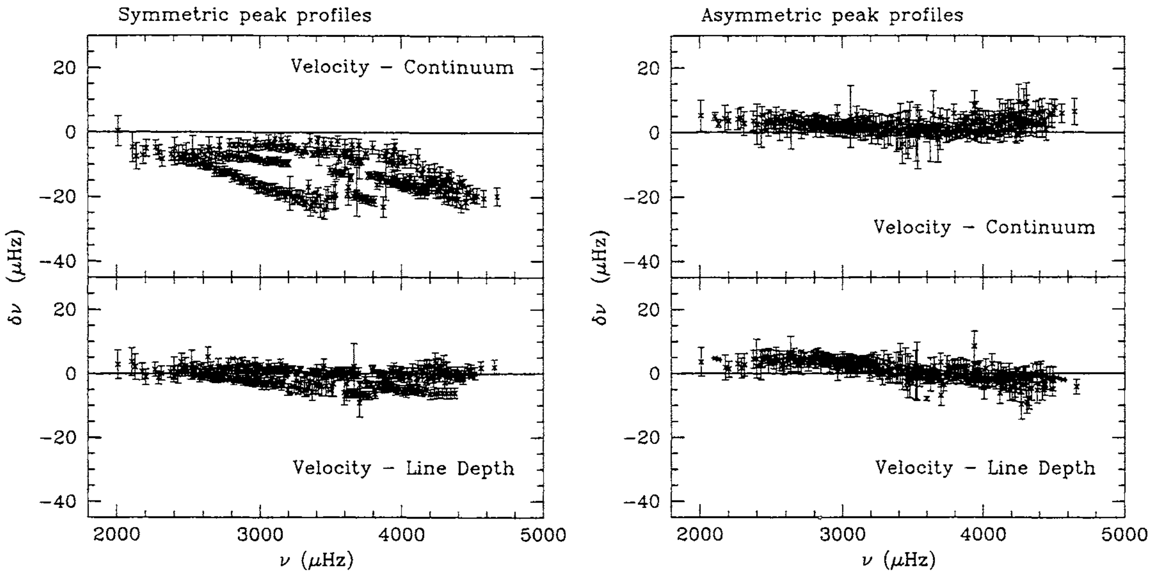

Figure 4. Frequency difference between modes fitted using different spectra, with symmetric and asymmetric peak profiles.

it is negative. This shift essentially gives the error introduced by assuming the peak profiles to be symmetric while fitting. It is clear that this shift is significantly larger than the estimated errors.

Fig. 4 shows the frequency difference between modes obtained from the velocity spectrum and the continuum and line-depth spectra using both symmetric and asymmetric peak profiles. Ideally one should expect all spectra to give the same frequency as the frequency of any mode should be independent of how it is observed. When symmetric peak profiles are used for fitting, there is significant difference between frequencies obtained from velocity and continuum spectra. This difference is significantly reduced when asymmetric peak profiles are used. However, there is still some systematic difference between frequencies computed using different spectra even when asymmetric peak profiles are used. It is possible that the form of asymmetry used in our model does not adequately represent the real profiles, particularly, in the velocity spectra where the signal to noise ratio is rather high. Between velocity and line-depth spectra there is not much difference as in this case the asymmetry is similar.

Fig. 5 shows the peak amplitudes in various modes obtained by fitting different 2d spectra. It is clear that in general this amplitude is largest for velocity spectrum, which makes it easier to fit these spectra. Nevertheless, at high frequencies where the power is low, the line-depth spectra appear to have a large amplitude. In addition to the amplitude, we can also compare the width obtained using different spectra. It turns out that there is very little difference in width in different spectra, which may be expected as the width is essentially a measure of life-time of the mode, which should be independent of how it is observed.

All the results mentioned above were obtained using fits to 2d spectra. We have also fitted the 3d spectra, but because of larger number of parameters and poor statistics

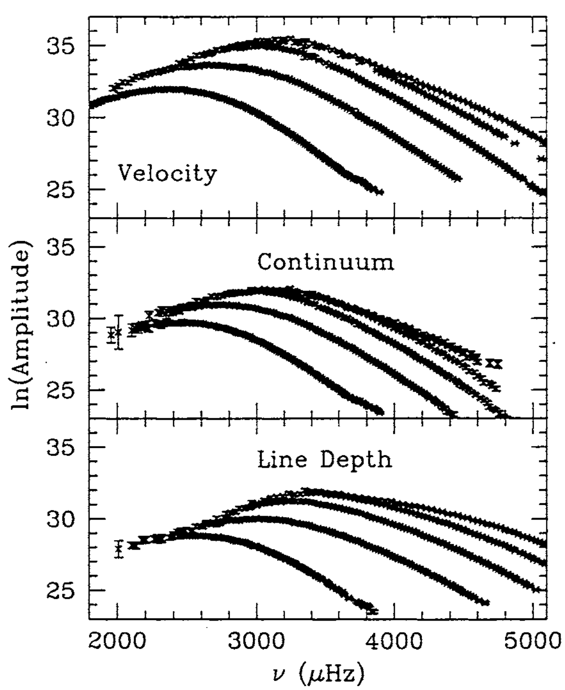

Figure 5. Amplitude of various modes, A_0 obtained from fits to different 2d spectra.

in the line-depth and continuum spectra it is difficult to obtain these fits. Fig. 6, shows the asymmetry parameter obtained from 3d fits to different spectra. This is similar to results obtained using the 2d spectra. For 3d spectra also use of asymmetry in peak profile leads to better

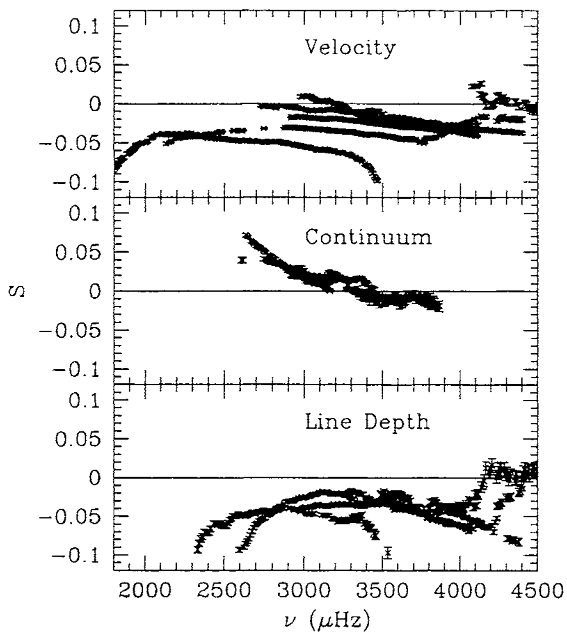

Figure 6. The asymmetry parameter, S obtained from fits to different 3d spectra.

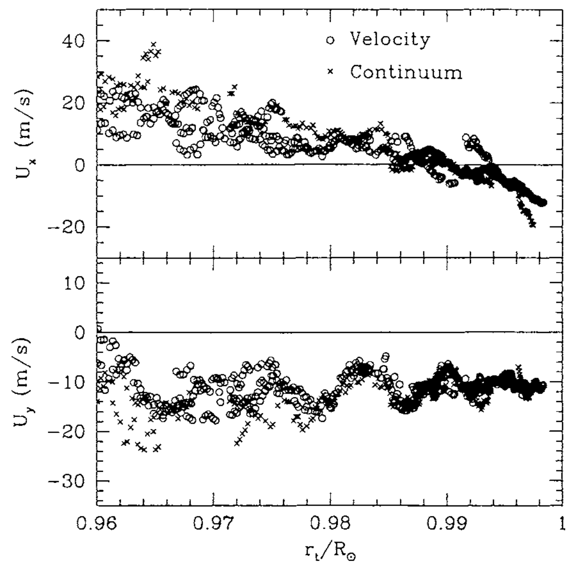

Figure 7. The horizontal velocity components U_x and U_y computed using the velocity and continuum spectra are compared. The results are plotted against the lower turning point of the modes.

agreement in frequencies computed using different spectra.

For 3d spectra we can also compare the fitted velocity components U_x and U_y for different modes and Fig. 7 compares these components obtained from the velocity and continuum spectra. There is good agreement between velocity estimated from the two spectra. The analysis of line-depth spectra is in progress.

4. CONCLUSIONS

The power spectra obtained from velocity, continuum and line-depth images all show distinct asymmetry in peak profiles. Use of symmetric profile tends to shift the estimated frequencies away from their true value by as much as 10 μHz. The velocity and line-depth spectra show negative asymmetry in peak profiles of most modes, while the continuum spectra show positive asymmetry. The asymmetry parameter in both cases is of order of 0.05 for modes with frequency near 3 mHz, where maximum power is found. The frequencies obtained by fitting asymmetric peak profiles to different spectra agree reasonably well with each other, while use of symmetric profile gives significant difference between frequency computed using continuum and velocity or line-depth spectra.

The amplitude as well as the peak to background ratio is highest for velocity spectrum and hence it is easier to fit these spectra. The width of peaks in power spectra do not depend on the type of spectra used in fitting. The width being a measure of life-time of modes should be independent of how it is observed. The asymmetry in 3d spectra also shows similar behaviour with velocity and line-depth spectra showing negative asymmetry and continuum spectra showing positive asymmetry. There is reasonable agreement between the velocity components computed from velocity and continuum spectra.

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REFERENCES

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

Antia H. M., Basu S., 1999, ApJ, 519, 400

Basu S., Antia H. M., 1999, ApJ, 525, 517

Basu S., Antia H. M., Tripathy S. C.,1999, ApJ, 512, 458

Hill F. 1988, ApJ, 333, 996

Nigam R., Kosovichev A. G., 1998, ApJ, 505, L51

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

Patrón, J., González Hernández, I., Chou, D.-Y., et al. 1997, ApJ, 485, 869