INTERMEDIATE DEGREE SOLAR OSCILLATIONS

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ABSTRACT. Spectra of solar intensity oscillations in the degree range ℓ = 20-98 were obtained with a 92% duty cycle over a 50 hour period from the geographic South Pole. After correction for solar rotation, the spectra have been averaged over azimuthal order m and fit with Lorentzian functions to provide values of background noise, amplitude, frequency and line width for 636 oscillation modes. The background noise is nearly independent of frequency in the range containing strong p-modes. The amplitude envelope shows little dependence on ℓ value and a frequency dependence similar to that of Doppler oscillations but shifted to higher frequency. Line widths increase at higher frequency and at higher ℓ values.

1. INTRODUCTION

The Sun's internal thermal structure has been effectively studied using measurements of the p-mode frequencies (Christensen-Dalsgaard *et al.* 1985). In particular, the speed of sound over much of the interior has been measured. This determination requires that the observed data be differentiated, a notably noisy process. It may be possible to measure the abundance of He in the convection zone (Däppen and Gough, 1986), but this would require differentiating the observed data twice. To prepare for future studies of these problems (and others) we have measured accurate p-mode frequencies for spherical harmonic degrees ℓ = 20-98. The unique aspects of the present determinations are 1) the lack of daily side lobes in the power spectra, the result of

* Visiting Astronomer, National Solar Observatory.
† Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

J. Christensen-Dalsgaard and S. Frandsen (eds.), Advances in Helio- and Asteroseismology, 37–40.

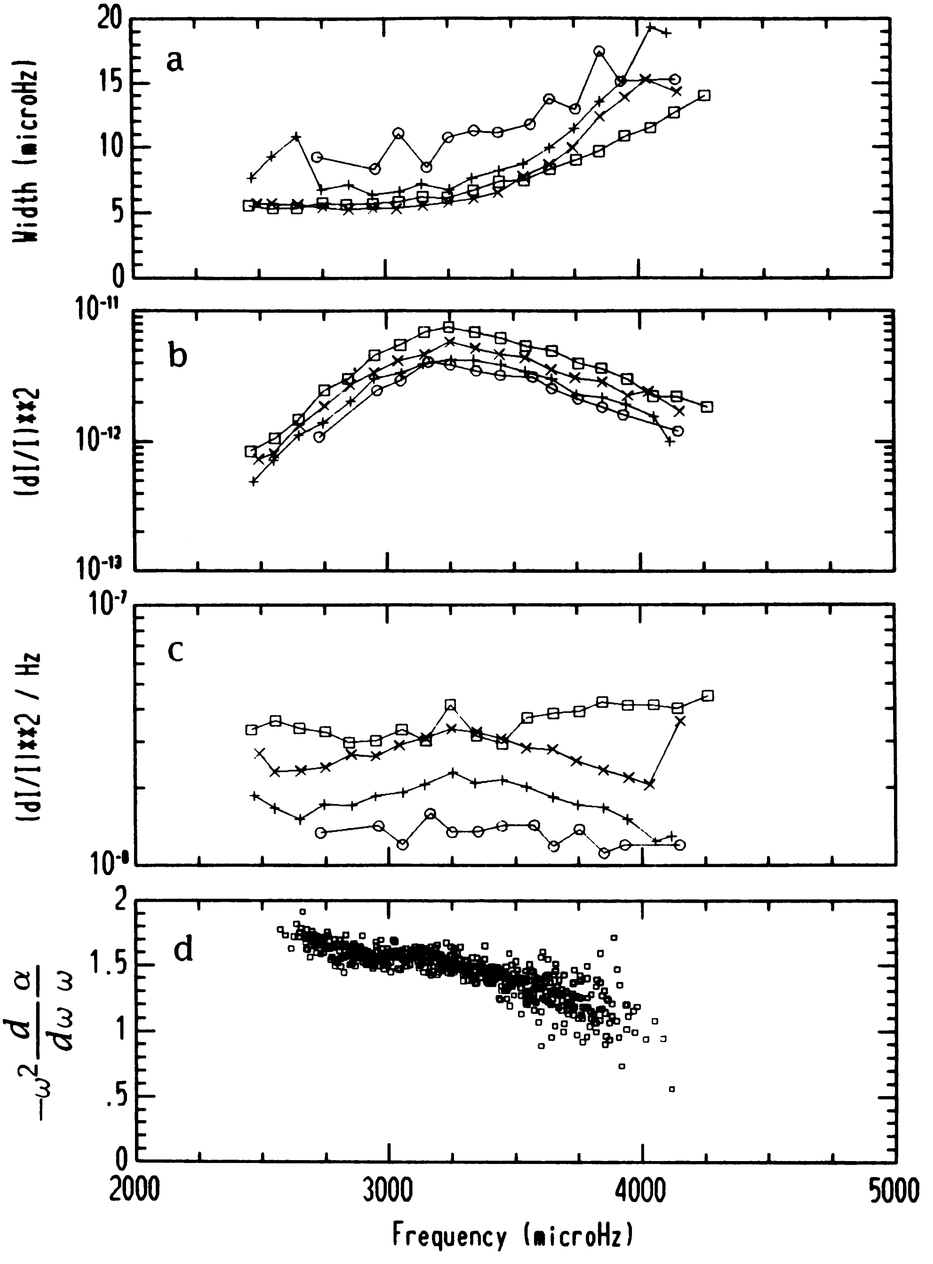

Figure 1. Quantities derived from individual Lorentzian fits to observed oscillation modes and averaged over ℓ ranges as follows: □ = 20-39, × = 40-59, + = 60-79, ○ = 80-98. (a) Full width at half maximum; resolution is limited to 5 μHz. (b) Integrated power per mode. (c) Background power density. (d) Phase shift estimates.

observing from the geographic South Pole during austral summer and 2) the use of spectra averaged over azimuthal order m, a technique introduced by Libbrecht and Zirin (1986). This technique results in a substantial increase in signal-to-noise ratio, about a factor of 9 at $\ell = 80$.

2. OBSERVATIONS AND ANALYSIS

The observations have been described elsewhere (Duvall, Harvey and Pomerantz, 1986) and will be only briefly summarized here. Full-disk images were obtained with a 0.6 nm filter centered on the CaII K line and a solid-state detector array having a resolution of ~10 arc s. The observations began 24 December 1981 at the geographic South Pole and extended for 50 h at 90-s sampling with 92% coverage, yielding a resolution of 5.6 μHz.

The initial data reduction is the same as described by Duvall, Harvey and Pomerantz (1986). Images are corrected for pixel-to-pixel variations of bias and gain. A low-degree fitting routine removes limb darkening, instrumental variations, and (unfortunately) low-spatial-frequency oscillations from the images. The images were interpolated onto a longitude - sine latitude grid and spherical harmonic coefficients were estimated in the manner pioneered by Brown (1985). Temporal power spectra were estimated in the normal way.

The mode frequencies are estimated from spectra averaged over the azimuthal order m. The averaging was performed with the solar rotation removed in the manner described by Duvall, Harvey, and Pomerantz (1986). Sections of the m-averaged spectra were fit using a weighted nonlinear least squares procedure based on the routine CURFIT (Bevington, 1969). Each data point in the fit is weighted by the inverse of the variance. The variance is estimated as the square of the mean signal divided by the number of spectra averaged. This variance estimate is based on the expected uncertainty in averaging different realizations of spectra with a common expectation value. The use of a least squares procedure based on Gaussian statistics is justified by the large number of spectra averaged and the central limit theorem.

The spectral features are fit by Lorentz profiles while the background over the fairly small frequency range is fit as a constant. The uncertainties in the fit coefficients are computed as diagonal components of the error matrix based on the variances mentioned above.

The region analyzed is similar to our previous rotation analysis between spherical harmonic degrees ℓ = 20-98 and frequency range ν = 2500-4000 μHz. We have analyzed only modes where the multiplet features are resolved.

3. RESULTS

Six hundred and thirty six modes were analyzed. In the center of the ℓ and ν ranges the random errors for mode frequencies are ~0.3 μHz. A table of frequencies would not fit in the present contribution and will be published elsewhere. The variations of the mode widths, integrated power and the background power density with frequency and spherical harmonic degree are shown in figure 1a-c. The data for these figures have been averaged in small frequency and degree ranges for clarity. In figure 1d is shown the variation with frequency of the phase shift of modes for the upper and lower reflections derived by the method of Brodsky and Vorontsov (1986). The mode linewidths exceed the observational resolution of 5 μHz at high frequencies and for higher degrees. This indicates relatively short lifetimes for modes of high frequency and high degree. The variation of integrated power per mode with frequency is similar to results of Doppler measurements made at lower degree (Libbrecht and Zirin, 1986) except that the envelope is shifted to higher frequency in the intensity observations. Background noise power density is nearly constant with frequency across the range of strong p-modes which indicates that a Lorentz function is a good model for the shape of the individual mode spectra.

Figure 2 shows the kernel for the asymptotic sound speed inversion (Christensen-Dalsgaard *et al.* 1986), dF/dw. F is the sound travel time across the radial cavity and w is the modal angular velocity. Notice the significant discontinuity in the middle of the curve. This appears to correspond with the bottom of the convection zone. A full inversion based on these data will be published elsewhere.

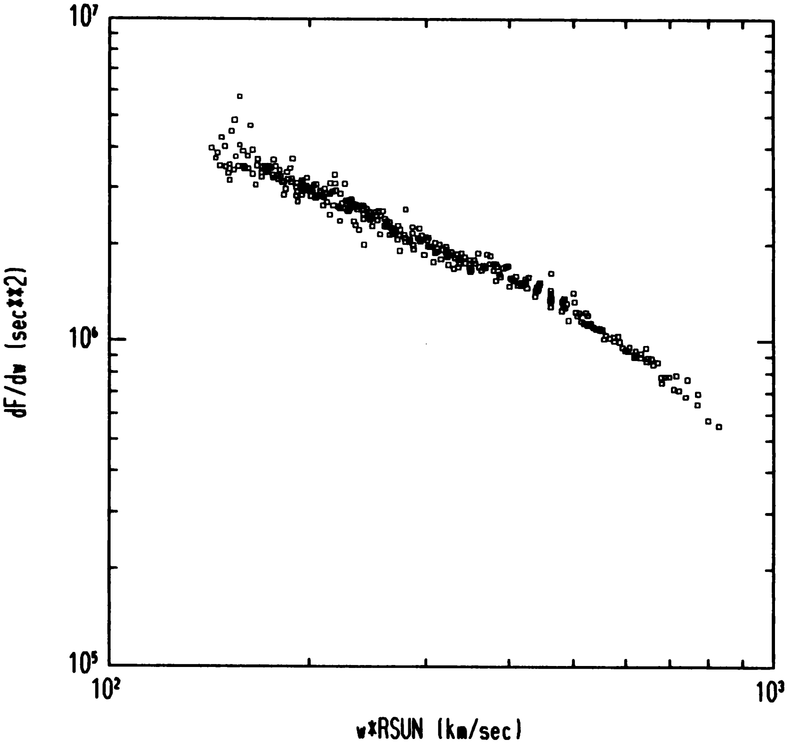

Figure 2. The quantity dF/dw is shown as a function of w, the angular velocity, times the solar radius. These data are the observational basis for a determination of internal sound speed.

4. ACKNOWLEDGEMENT

This work was supported in part by National Science Foundation grant DPP78-22267.

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