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Observation of Additional Low-Degree Five-Minute Modes of Solar Oscillation

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By measuring the difference between the shifts in the Fe 5124 spectrum line from light integrated from a central circular portion of the solar disk and from an annular

portion exterior to it, we have been able to detect high-order solar oscillations with degrees $\ell = 3, 4$ *and 5. The frequencies of the octupole modes agree well with the values obtained from whole-disk measurements at the South Pole*.[1] *A least-squares fit of the observed frequencies to values interpolated between and extrapolated from the predictions of a sequence of solar models with different chemical compositions selects a model with a helium abundance somewhat greater than 25 per cent by mass.*

Most of the previous observations of low-degree five-minute solar oscillations have been made with light integrated from the entire solar disk. Claverie *et al*.[2-5] and Grec *et al*.[6,7,1] have measured spectrum line shifts, and Deubner[8] and Woodard and Hudson[9] have measured radiant intensity. Such measurements are most sensitive to modes of degree ℓ = 0, 1 and 2; the long continuous Doppler observations made at the South Pole have also isolated octupole modes.[1]

Our observations are based on a method used by Severny *et al*.[10] A Babcock solar magnetograph[11] at the Stanford Solar Observatory, which is normally used for measuring Zeeman splitting, was converted into an instrument that measures Doppler shifts with equivalent sensitivity. For this purpose one selects a magnetically insensitive Fraunhofer line (with $g = 0$). Light from a central circular area of the solar disk, with radius 0.5 $R_\odot$, is filtered with a right-hand circular polarizer, and light from the annulus between 0.55 $R_\odot$ and 0.80 $R_\odot$ is filtered with a left-hand polarizer. The wavelength difference between the right and left polarized spectrum lines is measured by the magnetograph. It is interpreted, via the Doppler formula, as the difference between the averaged line-of-sight velocities from the circular and annular portions of the solar disk.[12]

Because our apparatus convolves the Doppler signal with a function whose length scale is less than the radius $R_\odot$ of the solar disk, the degrees of the modes of oscillation to which it is most sensitive are higher than for whole-disk observations. Our signal should be dominated by modes with $\ell = 3$, 4 and 5, though contributions from modes with $\ell = 2$, 6, 9 and 10 should also be detectable.[13] Here we concentrate on the dominant modes.

We obtained good quality data on 15 days from 17 June 1981 to 14 July 1981. The observations were made with 0.1 s time resolution, and were subsequently averaged into 15 s bins. A slow drift, typically of amplitude 1 m s per hour, was then removed with a high-pass filter. This left data sets over intervals of averaged duration 9.6 h. Harmonic amplitude spectra were computed from each data set using a simple least-squares method for finding Fourier coefficients in the frequency range 2.0 mHz - 4.5 mHz in steps of 1.0 μHz.

Figure 1 is the average of the 15 spectra. In common with previous observations, power is found to be concentrated between 2.5 mHz and 4.0 mHz, and appears to be generated by a series of oscillators with uniformly spaced frequencies. But whereas whole-disk observations with comparable resolution[2-4,8] display two peaks per interval of about 136 μHz (corresponding to a mode with $\ell = 1$ and an unresolved pair with $\ell = 0$ and $\ell = 2$), here, as expected, there are three; we infer that they correspond to modes with $\ell = 3$, 4 and 5.

By selecting every third peak (taking due account of peaks that are obviously missing), one might hope to collect sets of modes of like degree. There are no obvious distinguishing differences between the amplitudes and frequencies of the three sets so obtained, as one would expect theoretically. Therefore we cannot identify the modes using our data alone. It is possible, however, to identify the modes in the data obtained at the South Pole, by comparing the uneven frequency distribution and variable peak heights with theoretical expectations.[1,6,7,13-16] The frequencies of the modes inferred to have $\ell = 3$ are indicated by vertical lines in Figure 1. They can be seen to correspond with some of the peaks of our spectrum.

To facilitate identification of the modes responsible for our data, we present, following Grec,[17] an echelle diagram (Figure 2) of the frequencies of the peak maxima in Figure 1. Each frequency ν is reduced to a frequency $\nu_1+\hat{\nu}$ by subtracting from ν integral multiples of $\Delta\nu$, where ν_1 is some constant frequency and $\hat{\nu}$ is in the range $(0, \Delta\nu)$. The diagram is a plot of $\nu_0 \equiv \nu-\hat{\nu}$ against $\hat{\nu}$, the spacing $\Delta\nu$ having been chosen to give roughly the same values of $\hat{\nu}$ to modes of like degree. Thus $\Delta\nu$ is representative of the mean frequency differences between modes of adjacent order and like degree. More accurate estimates of these differences are given in the caption.

Included in Figure 2 are the octupole modes identified in the South Pole data. These agree well with one of our columns of frequencies, and therefore we deduce that this column also results from octupole modes. The degrees of the new modes producing the other two principal columns are then inferred by comparison with theory.[13] Further comparisons with theory and with other observations will be reported elsewhere.[18]

The addition of these new modes to the helioseismological data should impose tighter theoretical constraints on solar models. Here we simply compare the frequencies we have measured with the frequencies ν_λ interpolated between and extrapolated beyond the frequencies ν_A, ν_B, ν_C of the three solar models A, B, C of Christensen-Dalsgaard *et al.*[19] according to the formula

$$\nu_\lambda = \begin{cases} \lambda\nu_A + (1-\lambda)\nu_B & \lambda > 0 \,, \\ (1+\lambda)\nu_B - \lambda\nu_C & \lambda < 0 \,. \end{cases} \qquad (1)$$

Model A is a standard solar model with initial helium and heavy-element abundances $(Y, Z) = (0.25, 0.02)$; Models B and C have initial abundances (0.19, 0.004) and (0.16, 0.001) respectively, and have suffered contamination by heavy elements in and above the convection zone at a rate chosen to yield a present surface abundance: $Z = 0.02$. The least-squares fit of ν_λ with our frequencies ν represented in Figure 2 yields $\lambda = 1.26 \pm 0.12$; it also yields values for the orders n of the modes. Thus a model somewhat richer than Model A in helium and heavy elements is favoured. This result agrees with that of similar analyses of whole-disk data[15] and low-order modes detected as oscillations in the limb-darkening function[20]. It implies a relatively deep convection zone, and is thus consistent with analyses of five-minute oscillations of high degree.[21-22]

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Figure Captions

Figure 1 Average of 15 squared velocity amplitude spectra of data collected in June and July 1981. The vertical lines mark the frequencies of octupole modes measured by Fossat *et al*[1]. at the South Pole.

Figure 2 Echelle diagram of the frequencies between 2.5 and 4.3 mHz of low-degree modes, constructed with $\nu_1 = 72$ μHz and $\Delta\nu = 136.0$ μHz. The frequencies ν of the modes represented in the diagram are given by $\nu = \nu_0 + \hat{\nu}$. Crosses indicate the frequencies of the peaks in Figure 1. Circles represent octupole modes (with $\hat{\nu}$ near 20 μHz) and some dipole modes (with $\hat{\nu}$ near 100 μHz) observed from the South Pole by Fossat *et al*[1]. Thus by comparing our results with the South Pole data and with theory we identify the degrees of the modes responsible for the three principal columns; these are indicated at the top of the diagram. We presume the frequencies 3703, 3846 and 4258 μHz to correspond to dipole modes. The ordinate scale n' on the right is the order n of modes with $\ell \geqslant 3$, and is $n - 1$ when $\ell = 2$. This identification was obtained by the least-squares comparison with theory described in the text. Fitting regression lines $\alpha + \beta(n - n_0)$, with

$n_o = 22 - \frac{1}{2}\ell$, to the three principal columns of Stanford frequencies ν yields (α, β) = (3152 ± 1, 135.7 ± 0.3), (3140 ± 1, 136.2 ± 0.4) and (3117 ± 1, 136.5 ± 0.3) for $\ell = 3, 4$ and 5 respectively.

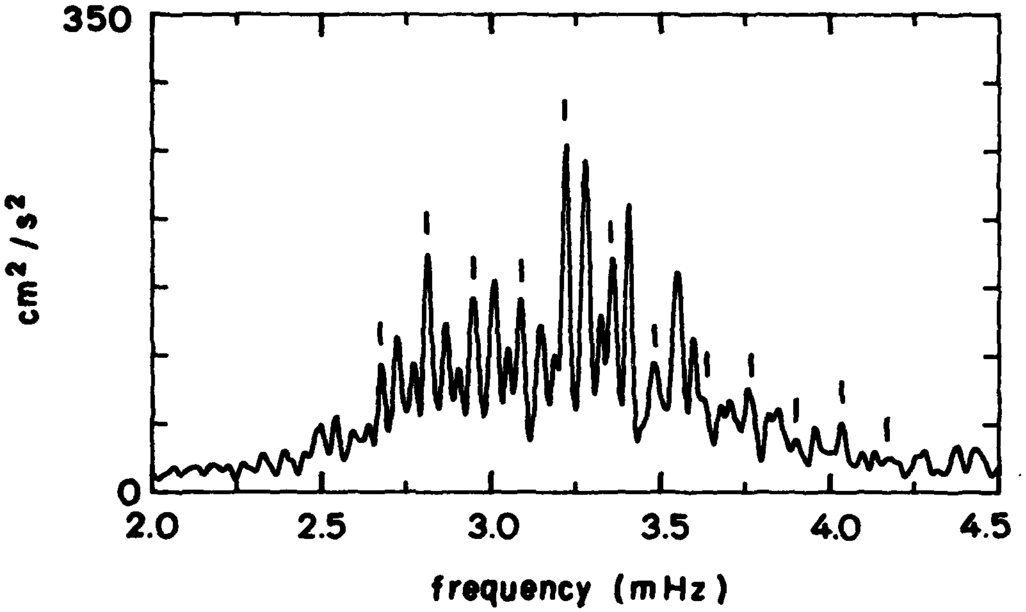
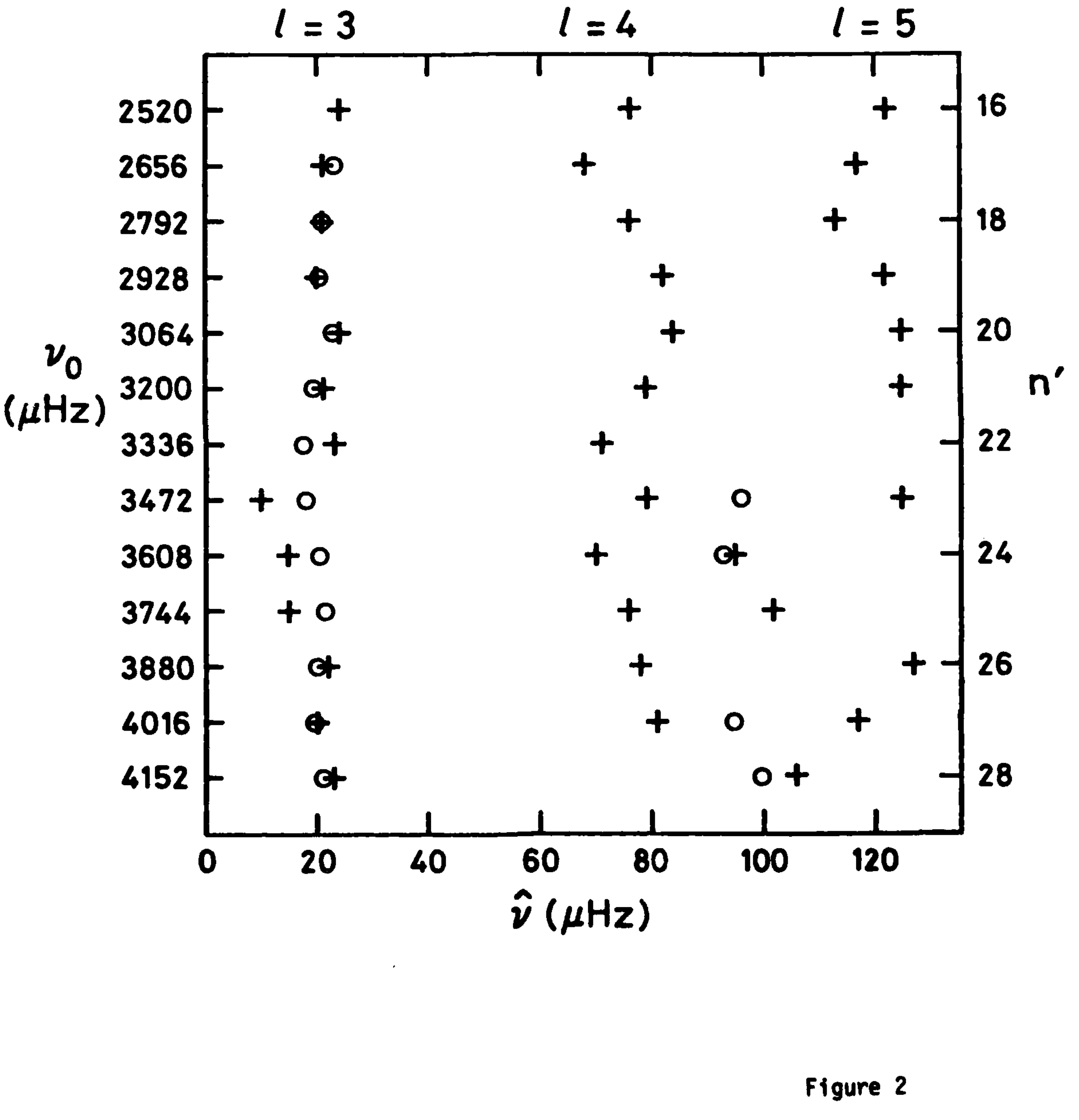


Figure 1



l = 3
l = 4
l = 5
ν_0 (μHz)
2520
2656
2792
2928
3064
3200
3336
3472
3608
3744
3880
4016
4152
16
18
20
22
24
26
28
n′
0
20
40
60
80
100
120
$\hat{\nu}$ (μHz)

Figure 2

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