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Observations of Low Wavenumber Nonradial Eigenmodes of the Sun*

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Summary. New photoelectric observations of the photospheric velocity field with high resolution in horizontal wavenumber and frequency have been carried out in the CI 5380 line. Three or four discrete stable modes of the five-minute oscillations are resolved in the k, ω diagram, which agree in many respects with the predicted fundamental modes of subphotospheric standing acoustic waves.

Some interesting aspects of the confirmation of a "global" excitation mechanism of the five-minute oscillations are pointed out. Several apparently discordant details of previous observations are rediscussed, and it is shown that they can be reconciled with the present results.

Key words: solar atmosphere — photospheric oscillations — nonradial eigenmodes

Introduction

Recent investigations of the horizontal scale of the five-minute oscillations, including both high resolution photographic and moderate or low resolution photoelectric techniques (cf. Stix and Wöhl, 1974; Deubner, 1974b; Fossat and Ricort, 1975), have unanimously and unambiguously confirmed the presence or rather concentration of oscillatory power at very low horizontal wave numbers $k=2\pi/\lambda<1\ \mathrm{Mm}^{-1}$. This finding, in accordance with the fact that spatial coincidence between granule appearance and the onset of an oscillation was not observed, (Frazier, 1968; Musman, 1974) and that almost no horizontal sound waves were found in the diagnostic diagrams of the photospheric velocity field (Stix and Wöhl, 1974), definitely rules out models of local excitation of the 5-min oscillations by granular pistons.

A different class of models, based on trapping of acoustic waves below the photosphere, had already been suggested and worked out in some detail by Ulrich (1970), Leibacher and Stein (1971) and Wolff (1972). These models are able to account for the existence of a pervasive wavemotion in a layer of the quiet solar atmosphere and in a frequency band where waves are essentially non progressive.

However, the "modal" character of these overstable subphotospheric oscillations, as predicted by theory, was not evident from the observations despite the considerable earlier efforts. This is not surprising, because the accumulation of data required for the computation of k, ω spectra with adequate statistical stability is enormous, and, moreover, the resolution in frequency *and* wavenumber achieved by previous writers was hardly sufficient for detection of even the lowest modes, as already pointed out by Ulrich (1970). We planned therefore a series of new observations, particularly designed to yield reliable information on the existence of any fine structure in the diagnostic spectra related to a modal character of the wavepattern. Our first attempts in this direction have proved successful, and the results will be described in this paper.

Observations

The low photospheric CI 5380 line ($EP=7.68$ eV) was used to measure Doppler velocities with the magnetograph of the Fraunhofer Institute attached to the domeless Coudé refractor in Anacapri. The total band pass of the exit slit was 20 mÅ. A straight line extending 300″ on the solar disk was scanned periodically at 110 s intervals with a 2.0 by 2.5 (arc s)^2 aperture. The scanning step was 1.0 arc s. At the beginning of each observation the scan line was centered on the disk centre, and then displaced continuously to correct for solar rotation.

We obtained two sets of observations, one lasting 2 h 50 m with the scan line running parallel to the solar axis, and a second one on the same day of September 20, 1974 lasting 3 h 55 m with the scan line parallel to the equator. With the exception of the small intersection area of the two scan lines, the two sets of data can be regarded as statistically independent.

The seeing conditions during this day remained moderate to poor and did not permit any high resolution work. The DC circuitry of the Doppler compensator, however, was perfectly stable, which enabled us to

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perform the observations of this extremely low contrast spectral line without difficulties.

Analysis and Results

Spatial and temporal averages of the measured velocity fluctuations were subtracted from the data before they were subjected to a straight forward FFT analysis followed by moderate smoothing (Hamming) of both frequency and wavenumber, and a second transform

$$P(k)=-k\cdot\int_{k_x=k}^{\infty}\frac{dP(k_x)/dk_x}{(k_x^2-k^2)^{1/2}}\,dk_x$$

which converts the Fourier spectra, under the assumption of two dimensional isotropy in space, into "diagnostic diagrams", yielding the correct power distribution per unit wave number. Final smoothing with 5-point running means in wavenumber k completes the numerical analysis.

Both sets of observations were evaluated separately, but finally plotted on the same scale in frequency ω, in order to facilitate the comparison between them (Fig. 1a and b). In the five-minute domain of the diagrams, the power distribution is given by contour lines outlining the increase of power in a quadratic progression. The striking similarity of some of the basic features in the two spectra and the appearance of discrete *stable* ridges in particular prompted us to combine (by adding) the results in one single spectrum which is plotted in the same way in Fig. 2.

This diagram makes it convincingly clear that the power distribution in the resonant range is not smooth in the sense that it decreases monotonically from a central maximum in all directions. A number of more or less parallel ridges running in a roughly diagonal direction at regularly spaced intervals can be easily seen. The gradient of these ridges (where they are well resolved, i.e. at $k\approx 1\,\mathrm{Mm}^{-1}$) corresponds to a horizontal group velocity of approximately $13\,\mathrm{km\,s}^{-1}$! This makes us aware of the potential importance of subphotospheric layers for the velocity field under consideration. The gradient further steepens as we approach lower wavenumbers (well visible in Fig. 1a).—At this point, we are prepared to compare our results with the theoretical predictions of trapped acoustic wave modes given by Ulrich (1970) and solutions for overstable modes of the entire solar body computed by Wolff (1974, unpublished results), which are also drawn in Fig. 2, *as given by the authors.*

In the "high wave number" domain we find that the solutions of Ulrich agree with the observed ridges in all detail to an embarassing extent. As well as a general family resemblance the observed and the predicted curves have the same curvature, appear at the same intervals and even, at almost precisely the same absolute position in k, ω space. The fundamental mode of Ulrich's also appears to be the first detectable mode in our diagram.

Obviously, our spectral resolution in k,ω space is insufficient, to resolve any of Wolff's radial eigenmodes which fall into the low wave number range of the diagram. However, it is interesting to note that 1. Wolff's modes appear to be the natural extension of Ulrich's (we have already pointed out the continuous increase of $d\omega/dk$ towards lower wavenumber in our data, and 2. the maximum of power of the combined observed spectrum clearly falls within the range of solutions

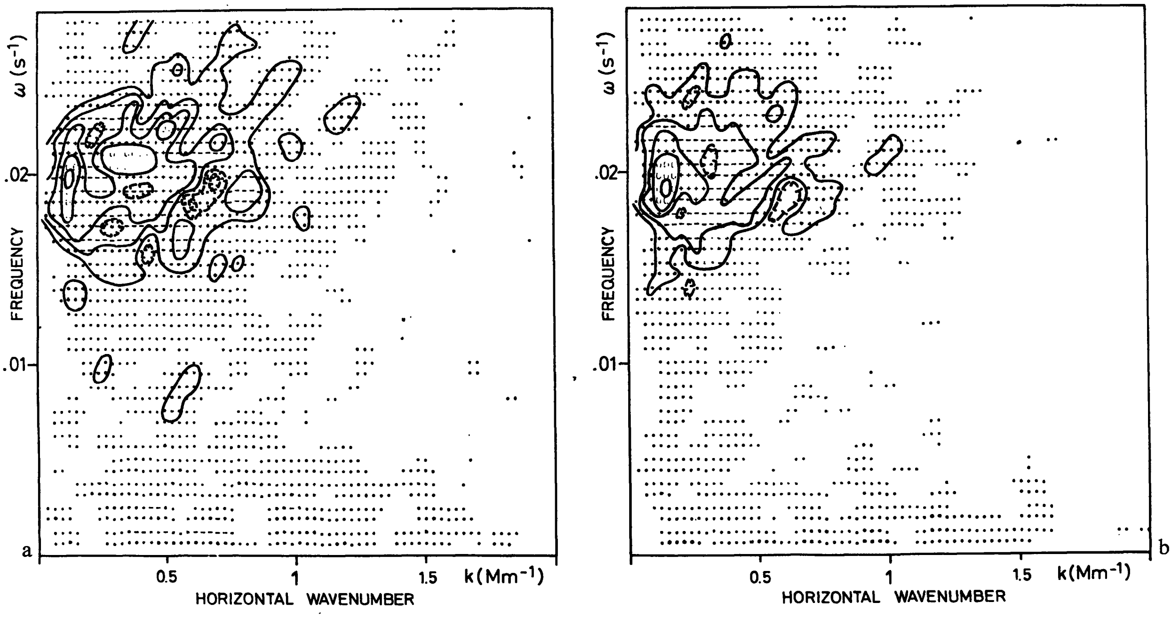

Fig. 1. (a) Diagnostic diagram of the photospheric velocity field computed from Doppler shifts of the CI 5380 line. Six different printer symbols bordered by solid contour lines indicate quadratically increasing levels of kinetic power per unit wavenumber, the lowest level printed (not outlined) being 2.8% of the maximum. Valleys are bordered by broken lines. (b) Same as 1a, obtained with different oriantation of the scan line

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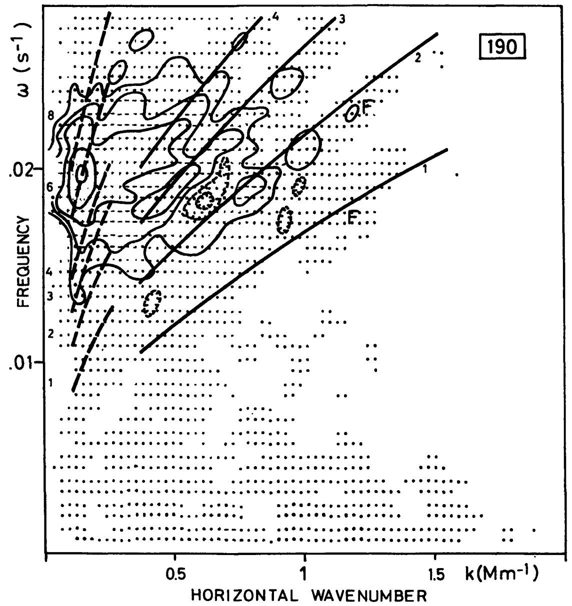

Fig. 2. Diagnostic diagram of the photospheric velocity field obtained by combining the statistically independent power spectra of Fig. 1a and 1b. The spectral resolution element with the number of "degrees of freedom" is given in the upper right corner. Predicted normal modes of trapped acoustic waves are drawn and their radial eigenvalues are given according to Ulrich (solid lines) and Wolff (dashed lines). The two power maxima observed by Frazier (1968) are indicated by a capital *F*

involving the entire solar body ($\lambda \approx 60''$). It is conceivable that, given a better resolution in k, we might be able to trace the resonant modes beyond the present limit of $k \approx 0.3\ \mathrm{Mm}^{-1}$. Observations exploring this part of the power spectrum are planned in the near future.

Discussion

We are now in the position to discuss a few of the apparent discrepancies found among previous observations of the five-minute oscillations without having to take one or the other side.

Since the oscillations evidently are a global solar phenomenon, we do not expect the oscillatory motion to be correlated to rising granules. Whenever such a coincidence was in fact observed (cf. e.g. Evans and Michard, 1962), it was probably due to the excitation of short period (<180 s) acoustic modes by powerful bright granules. The occurance of such modes has recently been demonstrated by Deubner (1974a). However, their contribution to the total power of the oscillatory velocity field is negligible.

It can be easily seen from the diagrams in Fig. 1, that the shape of one dimensional ω-spectra will depend on the choice of a particular spatial "window" just as much as on the amount of time spent for the observation. Applying a somewhat rigorous mathematical treatment to one-point records of the velocity field obtained by B. Howard, White and Cha (1973) have been able to produce a smooth "stable" ω-spectrum similar to the one obtained by Deubner (1972) by averaging a large number of statistically independent raw frequency spectra. But it is now becoming clear that physically the width of the resonance spectrum reflects the dispersion law and the growth rates of certain oscillatory modes in the deep solar photosphere rather than the randomness of the process.

Horizontal progression of the oscillatory motion at sound velocity has never been observed. The waves are standing also in horizontal direction. The resulting picture, comparable to the surface of an agitated pond, is easily confused with a closely packed field of independently oscillating cells, frequently put forward in the past. But, even with standing waves prevailing, interference of the different modes visible in our diagrams is inevitable in space and time. It is not surprising that the beat period (20–25 min) and spatial "coherence length" (15–30 Mm) derived from the observed differences in frequency and wave number among the oscillatory modes is in good agreement with the values obtained from previous one dimensional measurements [see White and Cha (1973), Wolff (1973), Fossat and Ricort (1975) for discussion of previous results]. An illustrative example of spatio-temporal interference patterns is discussed by Reif and Musman (1971).

Apart from interference phenomena particularly deceptive in a one dimensional treatment of small samples, it can be seen from the diagrams of Fig. 1, that even with a record length of ca. 3 h the distribution of power is neither uniform nor constant along the dispersion curves, and maxima appear at quite different horizontal eigenvalues at different times. This also applies to the principal maximum which changes drastically its position and structure from one record to the other. At present we are not able to distinguish between real temporal fluctuations of the distribution of power among different eigenmodes and a possible anisotropy of the wave field, seen with different orientations of the scan line.

Regarding the wide range in wavenumber k covered by the power spectrum, the whole dispute about the horizontal scale of the oscillation becomes void. Considerable amount of power is still present at $k \approx 1\ \mathrm{Mm}^{-1}$, corresponding to $\lambda = 9''$ or—in terms of diameters as discussed by Deubner and Hayashi (1973) and Fossat and Ricort (1975)—to a cell size of ≈ 2000 km, which equals the lower number given by Sheeley and Bhatnagar (1971). The fact that the small elements appear to be the most powerful in the spectro-heliograms is a consequence of the presentation in λ-space with $d\lambda = -\lambda^2 dk$. The maximum of the power distribution per unit wavenumber clearly is at the limit of our spectral resolution close to $\lambda = 60''$, confirming the large numbers derived from most of the photoelectric measurements.

In their resent study of the photospheric oscillations,

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Fossat and Ricort (1975) reported on a secondary power maximum at periods of 10 min, which they occasionally found in the frequency spectra deduced from recordings with apertures larger than 3 arc min. In Fig. 1b of the present paper two "modes" appear which are probably related to this feature, one at $k=0.25\,\mathrm{Mm}^{-1}$ on the extension of Ulrich's fundamental mode (or a zero mode of Wolff's) and another one at $k=0.55$ occupying the locus of a hypothetical zero mode of Ulrich's solutions. Since such a zero mode is physically meaningless in the context of Ulrich's work (it requires one open boundary) the presence of such a mode in the data would indicate that the model atmosphere used by Ulrich still needs some corrections. Of course, more observations are desirable to verify this particular mode.

It is interesting to note, that neither of the two 10 min modes appears in the other diagram 1b, thus confirming the spasmodical character of the 10 min oscillations, reported by Fossat and Ricort. The large spatial coherence length (100 Mm) estimated by these authors is not evident from our spectra.

Is there horizontal phase propagation at high velocities? Deubner and Hayashi (1973) have argued that phase velocities of the order of $140\,\mathrm{km\,s}^{-1}$ reported by Musman and Rust (1970) can be easily interpreted as random phase relations of adjacent independent oscillators. Now that we have confirmed the global character of the wave field we are entitled to compare this value measured in λ-space with the ratio of $\omega_{\mathrm{MAX}}/k_{\mathrm{MAX}}$ taken from the combined spectrum in Fig. 2. With $\omega_{\mathrm{MAX}}=2.1\times10^{-2}\,\mathrm{s}^{-1}$ and $k_{\mathrm{MAX}}=0.144\,\mathrm{Mm}^{-1}$ we obtain $v_{\mathrm{phase}}=145$ km in excellent agreement with the previous number.

Frazier (1968) had already observed a decomposition of the oscillatory power distribution into two separate maxima at periods of 270 s and 360 s. Since the spatial as well as the temporal window of his observations were rather small, serious doubts were raised about the statistical reliability of his results, and it remained an open question, whether the two maxima could be identified with eigenmodes of the solar atmosphere. If we believe that randomness in the velocity field is restricted to fluctuations of power along a given set of discrete "modes" in the spectrum, there is no reason to discredit Fraziers results as a first indication of the modal character of the five-minute oscillations. The maxima taken from his Fig. 3c are indicated by capital F in our Fig. 2. They can be seen to coincide closely with the ridges belonging to the first two eigensolutions given by Ulrich (1970). Again, it is mainly the correct *spacing* of Fraziers modes which gives us the confidence of not having stretched the argument too far.

Conclusions

Our observations have shown that the five-minute oscillations may in fact be interpreted as low wavenumber nonradial acoustic eigenmodes of the subphotospheric layers of the solar atmosphere.

Many of the hitherto seemingly discordant observational aspects of the five-minute oscillation can be reconciled in this interpretation quite naturally. The concentration

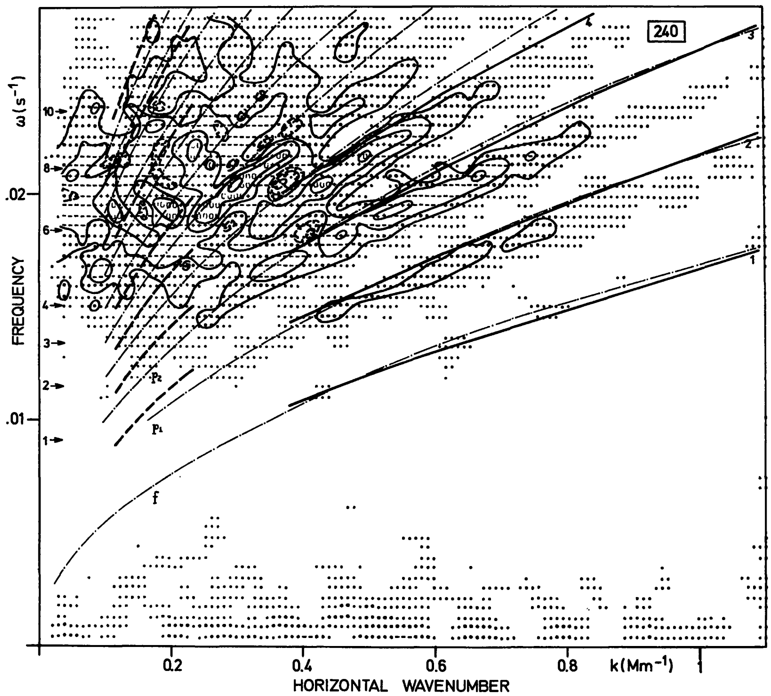

Fig. 3. Diagnostic diagram as in Fig. 2, obtained from observations with a 880 arc s scan line. The dash dotted curves delineate the solutions obtained by Ando and Osaki (1975)

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of power at very low wavenumbers indicates that substantial parts of the solar interior participate in the oscillation. A direct comparison of our observations with the spectra of free (without artificial boundary) normal modes of oscillation of the whole sun has not yet been possible because of lack of spectral resolution. But the necessary resolution can certainly be achieved in the near future, putting at our disposal an excellent diagnostic tool which allows us to probe the internal structure of our sun as we can the structure of pulsating stellar variables.

Since the five-minute oscillations very likely contribute significantly to the heating of the upper chromosphere and corona (for a review of literature see Stein and Leibacher, 1974), it seems desirable that the production of this energy flux which has to be supplied continuously and over the whole surface of the sun, does not depend on localized events of a shallow surface layer. The observations provide sufficient evidence that this basic process of the solar envelope is indeed deeply and firmly rooted in the solar body.

Note: Another set of four-hour recordings of the solar eigenmodes was obtained recently (June 1975) with a larger scan line extending across half the solar diameter. The average k, w diagram resulting from three such recordings is plotted in Fig. 3. Due to the high spectral resolution achieved, more than five modes may be traced down to wavenumbers as low as 0 s Mm^{-1}, and can be compared with the theoretical predictions.

We also included in this graph the new results of Ando and Osaki (1975, to be published) who solved the equations of linear *nonadiabatic* nonradial oscillations of the solar envelope. We note that with increasing modal index their solutions (as well as Ulrich's) tend to deviate progressively from the observed positions of the individual modes. We suppose that the model of the outer layers of the convection zone used in the calculations still needs further improvement.

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