PHASE-SPECTRA OF SOLAR OSCILLATIONS

J. Staiger (1), B. Schmieder (2), F.-L. Deubner (3) and W. Mattig (1)

(1) Kiepenheuer-Institut für Sonnenphysik, Freiburg, BDR
(2) Observatoire de Meudon, France
(3) Institut für Astronomie u. Astrophysik d. Universität, Würzburg, BDR

Abstract: Diodearray-measurements of intensity- and velocity-oscillations were made at the Coudé-telescope of Capri. From these observations phase-spectra were calculated to identify different types of waves within the solar atmosphere. The results indicate the existence of atmospheric gravity modes in the frequency-range below 2.5 mHz. No running acoustic waves were found in the photosphere for frequencies beyond 7.5 mHz. Vertical propagation seems only to take place for frequencies between 5 mHz and 7.5 mHz. No vertical propagation at all was found in the upper chromosphere. This seems to be due to the occurrence of wave reflection at the chromosphere-corona interface.

1. Introduction

Several problems related to the vertical propagation of oscillations in the solar atmosphere have not yet been solved completely. One example is the heating of the upper atmospheric layers by oscillations. Another one is the separation of oscillations and convective motions in the k-ω-diagram and the identification of atmospheric gravity modes. The published results about the evidence of gravity waves in the solar atmosphere do not coincide completely with each other. The same is true for the supposed existence of propagating acoustic waves in the photosphere and chromosphere. One of the methods to investigate these problems is the observation and computation of phase-relationships. It is possible to measure either phase-differences between velocity-oscillations at two different atmospheric height levels (V-V-spectra) or between intensity- and velocity-oscillations at the same level (I-V-spectra). Together with theoretical calculations both types of phase-spectra can help to get information about propagation and dissipation mechanisms within the atmosphere.

2. Observations

The principle of measurement is very simple and consists of the following steps (V-V-spectra):

a) Choose two spectral lines with different height of line formation
b) Measure simultaneously the doppler-displacements of both line cores
c) Calculate Fourier-transforms of both velocity time-series
d) Compare the phases of the Fourier-components and calculate the phase-difference for each frequency
The observations were made with linear 1024-diode Reticon arrays. The arrays were arranged perpendicular to the direction of dispersion as shown below:

They were shifted periodically across the line centers to measure Doppler-shifts and intensity-fluctuations in the line cores. All observations were made at the center of the quiet sun.

3. Experimental results

Gravity waves

Theoretical calculations show that in the presence of gravity waves vertical phase-velocities should be directed radially inward (that means that V-V-phase-differences between two layers with increasing height are negative). First evidence of such negative phase-values was found by B. Schmieder (1976). But the statistical significance of this result was not extremely high and it could not be reproduced by Lites, Chipman (1979) with improved instrumentation. So this problem could not be regarded as completely solved. It was therefore re-examined with the diode arrays. Fig. 2 shows one of the observational results:

Negative phase-differences are evident below 2.5 mHz. Comparison between observational and (dashed) theoretical data shows good coincidence between 2 mHz and 3 mHz (for details of theoretical calculation see B. Schmieder 1976). The double minimum at ~0.7 mHz and ~1.9 mHz is a newly observed feature. It also showed up in several other V-V-spectra. It cannot be explained by the
existing theories. Under the assumption that the theoretical identification of negative phase-differences with gravity waves is correct, it may be attributed to a double excitation of gravity oscillations by granulation (1.9 mHz) and by slow chromospheric movements, which reach down into the photosphere (0.7 mHz). But this is just speculation and may be completely wrong. More detailed theoretical calculations have to be done.

Propagating acoustic waves

The possible existence of running waves can be examined either by V-V-spectra or by I-V-spectra. Under the (occasionally crude) approximation that temperature fluctuations can be identified with intensity fluctuations and the assumption of standing waves below and running waves beyond the acoustic cut-off frequency \( \omega_{ac} \), we can expect an I-V-phase-spectrum as shown on the right. (gravity waves and the influence of radiative dissipation are neglected). The intensity oscillations lead the velocity oscillations by 90° in the standing wave domain and approach 0° asymptotically beyond \( \omega_{ac} \). Under non-adiabatic conditions (eg. in the photosphere where radiative relaxation takes place) the phase values are higher than 90° (\( \omega \approx 130° \)). But still we should see an asymptotical decrease in the running wave domain. So far such a behaviour has not been observed unambiguously. The published results are widespread and don't give a satisfying selfconsistent picture. To improve this situation several I-V-spectra were measured. Example:
The preceding phase-spectrum of the Fe I - line \( \lambda = 5930 \ \AA \) represents the photosphere at a height level of approximately 200 km (Durrant 1982). The steep phase gradient at \( \sim 2.4 \) mHz may be attributed to the changeover from gravity to acoustic modes, although no detailed theoretical calculations exist about the I-V-phase behaviour of gravity waves. But the change of sign happens to be at approximately the same frequency, as it was the case in the V-V-spectrum of Fig. 2. Beyond the local maximum of \( \sim 135^\circ \) at 4.5 mHz the phase-difference slowly falls off with frequency as predicted by theory for running acoustic waves. For frequencies \( > 7.5 \) mHz the curve remains at a level near \( 90^\circ \pm 30^\circ \). This cannot be explained by running waves. Examination of several V-V-spectra lead to similar results. Example:

![Spectral Distribution of Phase-Differences](image)

Between the acoustic cut-off frequency (\( \sim 5 \) mHz) and 7.5 mHz the V-V-curve shows a near linear rise which is typical for vertically propagating waves. Then it drops off to 0°. Standing waves may be responsible for this decrease. Fig. 4 and Fig. 5 both show that it was possible to improve frequency resolution and precision of phase spectra with the help of diode arrays compared to earlier results.

Chromospheric wave propagation

Athay a. White (1979) found evidence of running waves in the chromosphere for frequencies beyond the acoustic cut-off frequency by observing UV-emission lines. This is not in agreement with the results of P. Mein (1971), N.a.P. Mein (1976) and Lites a. Chipman (1982), who all found very small phasedifferences which could not be explained by acoustic wave propagation. The solution of this problem is important in connection with the oscillatory contribution to the energy balance of the chromosphere. With that in mind chromospheric phase-spectra were observed again with the diode arrays. The following example covers the height range between 1200 km (\( \lambda = 8498 \ \AA \)) and 1600 km (\( \lambda = 8542 \ \AA \)) (Schleicher 1976).

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In the whole acoustic frequency range the phasedifferences are close to 0° (notice vertical scale) and much too small to be explained by vertically propagating waves. This confirms the results of N. Mein, P. Mein, Lites a. Chipman. An interesting new feature is the oscillatory behaviour of the phase-curve beyond 5 mHz which also showed up in other phase-spectra. It is not yet clear whether this is of solar origin (caused by wave reflections) or if it is nonsense. Additional observations with different instrumental configuration are necessary. A possible explanation can be found in another paper of this book (Deubner, Endler, Staiger).

There is an obvious difference between the V-V-spectra of the photosphere and the chromosphere. The photospheric running waves have disappeared at the higher chromospheric levels. This may be due to the fact that they loose their internal energy into the chromospheric 3-minute oscillations cavity. Velocity power spectra of the line λ = 8542 Å showed strong excitation of oscillations in the 3-minute range (~6 mHz) which could not be detected at deeper atmospheric levels. But the final answer to this problem has to be postponed until more detailed calculations about oscillatory energy dissipation and observations with better vertical height resolution are available.

To explain the small chromospheric phase-lags N. Mein, J. Provost (1977, 1978) and B. Schmieder (1978) made the proposal that running waves could be reflected at the chromosphere-corona interface and build up standing waves with horizontal nodal planes. Under this assumption we should see a 180°-phasejump in the I-V-spectrum near 8 mHz as shown to the right (for details see Mein, Provost, Schmieder). For the first time such a phasejump could be detected now in an observational I-V-spectrum (Fig. 8):
This phase jump can be explained by the intersection of the (usually different) heights of formation for intensity- and velocity fluctuations with the horizontal nodal planes of the standing waves. By simply calculating vertical wavelengths it is possible to show that the heights of formation of the chromospheric lines $\lambda = 8498 \AA$ and $\lambda = 8542 \AA$ are free of horizontal nodal planes. And in fact no phase jump appeared in the I-V-spectra of these lines. For the same reason no $180^\circ$ discontinuity can be seen in the V-V-spectrum of Fig. 6.

Conclusion: Diodarray-instrumentation proved to be useful in improving frequency resolution and precision of phase-spectra. The low-frequency behaviour of V-V-spectra indicates the existence of atmospheric gravity modes as already proposed earlier by B. Schmieder. Photospheric phase-spectra show evidence of propagating acoustic waves in the frequency range between 5 mHz and 7.5 mHz. Chromospheric data seem to indicate reflection of running acoustic waves at the chromosphere-corona interface, as theoretically proposed by N. Mein, J. Provost and B. Schmieder. This has the consequence that coronal heating by acoustic waves does most likely not happen (at least below 10 mHz).

The results presented here will be published in more detail as soon as possible.

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