CHAPTER 7

OSCILLATIONS IN THE SOLAR ATMOSPHERE

DIAGNOSIS OF THE SOLAR ATMOSPHERE USING SOLAR OSCILLATIONS

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ABSTRACT. I present a review of the art of using acoustic and gravity waves as a tool to probe the structure of the solar atmosphere. The principle ideas behind the technique are discussed and a small bouquet of results is presented. The current discrepancies are pointed out, and in the last section a few thoughts are let loose about the inversion of data to deduce the physical state of the atmosphere.

1. INTRODUCTION.

In the early sixties when the 5 minute oscillations were first detected, the subject was thought to be mainly an atmospheric discipline. The next decade a lot of work was done to understand and use observations of oscillations to explain characteristics of the solar atmosphere (chromospheric heating f.ex.). However when it was realized in the early seventies, that the oscillations represented true global modes, the interest changed quickly towards the exciting possibility of doing seismology on the Sun by measuring accurate periods for the p- (and g-)modes. Thus still today the full potential of the oscillations as a tool to infer the physical state of the atmosphere has not yet been fully exploited. Let me try to convince you in the limited space available, that the previous statement is true, by going through the following sequence of sections:

a. Properties of waves in an isothermal atmosphere
b. p- and g-modes in a real atmosphere.
c. Outline of the existing observational database.
d. Interpretation of the observations.
e. Inversion of the data to obtain the structure of the atmosphere

But before leaving the introduction let us very shortly define the regions and the waves to be discussed later. Fig. 1 shows where waves can propagate in the Sun. Let ω_{ac} be the acoustical cutoff frequency, and S_l the

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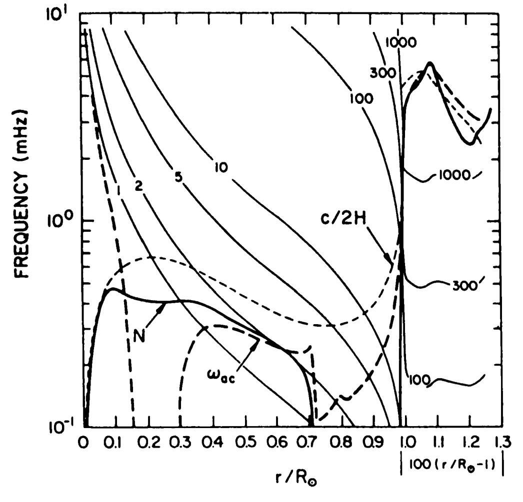

Fig. 1. N_{BV}, ω_{ac} and S_l are plotted as function of fractional radius. The isothermal sound speed is the curve labeled $c/2H$. Notice the scale change at $r/R_\odot=1$. (Brown et al.,1985)

frequency, which defines the turning point of a non-radial mode:

$$S_l^2=c^2k_x^2 \qquad (1)$$

where c is the local sound speed and k_x the horizontal wavenumber: $k_x^2=l(l+1)/r^2$ of the oscillation. Acoustic waves can become trapped between the S_l and the ω_{ac} curve in the interval where $\omega>S_l$ and $\omega>\omega_{ac}$. There are 2 regions both visible from the Earth. One extending from the turning point in the interior to the temperature minimum in the photosphere, where waves leak through, and one on the other side of the temperature minimum with the transition region as the outer boundary. Gravity waves can propagate in the small region above the photosphere where the Brunt-Väisälä frequency N_{BV} has a maximum.

2. THE ISOTHERMAL ATMOSPHERE.

As soon as the 5 minute modes had been identified, the theory for acoustic and gravity waves in an isothermal atmosphere was developed in detail and applied to the new feature observed in the Sun. This quickly gave a first understanding of the behaviour of the oscillations. Noyes and Leighton as early as 1963 published formulas and tables for amplitude ratios and phase differences of intensity and velocity measurements, which were compared with the first data. Souffrin added to the analysis a couple of very thorough papers (1966, 1972), and several other people have contributed (i.e. Stein and Spiegel, 1967, and Zhugzdha, 1984).

Let γ be a constant. Then the following other quantities are constant as well:

The sound speed c given by

$$c^2=\gamma g H \tag{I}$$

The acoustical cutoff frequency

$$\omega_{ac}=c/2H \tag{3}$$

and the Brunt-Väisälä frequency

$$N^2=\frac{\gamma-1}{\gamma}\frac{g}{H} \tag{4}$$

where g is the gravity in the atmosphere, H the scale height. We also define the relaxation time τ_R by writing the heat loss (by radiation assuming Newtons law of cooling) as

$$q'=-\frac{c_p}{\tau_R}T' \tag{5}$$

where T' is the Eulerian temperature perturbation and

$$\tau_R=\frac{c_p}{4ac\kappa T^3} \tag{6}$$

Let us look at the vertical variation of the waves. If τ_R is much larger than the period of the waves, the waves are adiabatic. As the density falls off with height as

$$\rho\approx e^{-z/H} \tag{7}$$

we get for progressing acoustic waves ($\omega>\omega_{ac}$), that the velocity amplitude

$$v\approx e^{z/2H} \tag{8}$$

because the kinetic energy $\approx\rho v^2$ is conserved. Thus the amplitudes of acoustic waves generated in the turbulent convective zone grows considerably as they travel upwards until they form shocks high in the atmosphere.

For evanescent waves, that are tunneling out from the hot interior, there is an extra factor

$$|v^2|\approx e^{-\beta z/H} \tag{9}$$

where in the adiabatic case β is given by

$$\beta=\sqrt{1-\omega^2/\omega_{ac}^2} \tag{10}$$

β defines the damping per scale height. The largest β is obtained for the smallest ω, which for acoustic waves is given by the condition $\omega>N_{BV}$, so that

$$\beta_{max} = \sqrt{1-4(\gamma-1)/\gamma^2} \tag{11}$$

For γ=5/3 β<<1, but for $\gamma \to 1$ the damping eliminates the exponential increase derived before.

Radiative damping has very little influence on the evanescent waves as can be seen in Fig. 2, but it becomes important for traveling waves. The importance is a function of the product $\omega_{ac}\tau_R$, which labels the curves in Fig. 2. For small values of τ_R considerable spatial damping sets in, $\beta \simeq 1$.

Of course dissipation will make the amplitude increase slower with height in the atmosphere than in the dissipationless case. Small frequencies or large damping give smaller amplitudes at the surface of the Sun.

Introducing dissipation also changes the amplitude ratio between the intensity and velocity and the phaselag of maximum outward velocity (blue-shift) to intensity (or temperature). The phaselag is shown in Fig. 3. The adiabatic result for the phase lag is respectively 0° and 90° for traveling and evanescent acoustic waves. Introducing radiative dissipation increases the phase lag, so that we expect the phaselag φ>0° for traveling waves and φ>90° for evanescent waves.

Another type of dissipation, which has only recently been discussed in detail by Brown (1984) and Durney (1984), is the dissipation due to turbulent viscosity in the convective region. The effects are difficult to predict, but

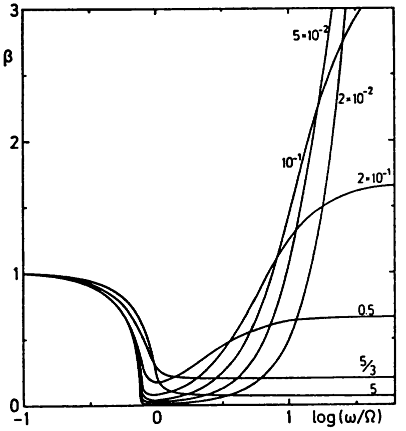

Fig. 2. Damping per scale height for γ=5/3. The curves are labeled by $\omega_{ac}\tau_R$. Gravity waves are to the left, evanescent waves in the middle and traveling waves to the right. β is defined in the text. (Souffrin,1972)

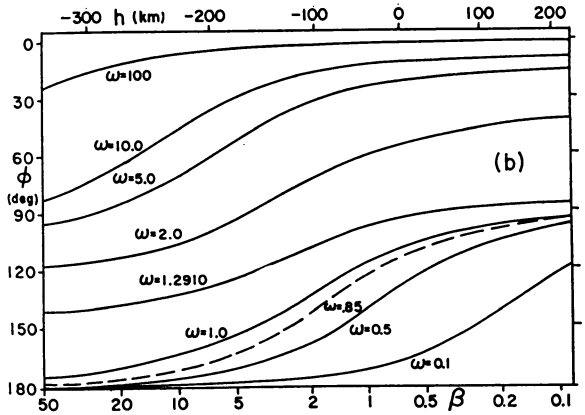

Fig. 3. Phaselag of blueshift to temperature in an isothermal atmosphere. The frequency ω is in units of ω_{ac}. The horizontal axis is $1/\tau_R\omega_{ac}$. (Noyes and Leighton,1963)

one would expect, that the effective sound speed would be reduced and that some energy would be scattered away from one mode. An incident plane wave will become wiggled in the turbulent region, which makes the distance through the region larger. This corresponds to a decrease of sound speed. How the phaselags behave I can not tell from any simple principle.

3. THE REAL ATMOSPHERE.

In a real atmosphere there are some important differences from the isothermal model. The scale height H is not constant and therefore none of the quantities defined in (2)-(4). g-modes are still not expected except maybe in the small cavity in the chromosphere where the relaxation time is long. But the g-modes tendency for horizontal propagation makes it difficult to set up standing waves in the inhomogeneous chromosphere.

Two types of acoustic waves are observed, the evanescent standing waves or the p-modes and the upward traveling waves generated in the turbulent convective region just below the photosphere. The amplitudes of the p-modes at a particular point in the atmosphere depends on the amount of energy fed into the mode and by the spatial structure of the eigenfunction. From the previous discussion we expect an increasing amplitude with height. The high frequency p-modes will show larger variation with height than lower frequencies because the vertical wavelength is shorter. Observing at high altitudes in the solar atmosphere one should see a shift towards higher frequencies of the p-mode spectrum. The velocity amplitude should not be affected by radiative effects, whereas the intensity signal at high altitudes might be sensitive to the radiation.

The phase of the evanescent modes is a complicated observable to describe. If there was no damping all velocities would have the same phase. The temperature would lead the velocity by 90°. Values greater than 90° are expected for the Sun, but as described later one is observing average values for a slab of the atmosphere. It is not always possible to explain the phases in terms of the isothermal results.

For progressing waves the very high frequencies are buried in the noise from seeing. The observable waves progress out to where they form shocks. This altitude decreases with increasing frequency. The phaselag of the velocity relative to intensity increases from close to 0° for high frequencies to the values for evanescent waves at the cutoff frequency.

Looking at the problem in more detail we have waves with long horizontal wavelength compared to the structures in the atmosphere, which is an inhomogeneous medium penetrated by narrow magnetic flux tubes. Due to the long wavelength the waves 'feel' some type of an average Sun at each depth in the atmosphere. The question is of course how this mean Sun is related to the mean Suns obtained by other techniques, like solar models (using mixing length theory) or semi-empirical models like the VAL-model or the average model from hydrodynamical calculations as presented by Nordlund (1984). The problem has the extra flavour to it, that the inhomogeneities (the convective eddies) themselves quite possibly drive the oscillations.

4. SKETCH OF THE EXISTING DATA FOR P- AND G-MODES.

What do we actually observe, when we look at the Sun? The first result I could find, of the determination of a phase difference between velocities at different altitudes, was a delay of the MgI line relative to the TiI line of 8.4 seconds given by Evans and Michard (1962); in degrees this is 10°. Deubner (1974) works it out in more detail and gets quite small values for different pairs of lines ($\Delta\varphi<5°$ except for the pair Hα and NaI, where $\Delta\varphi\approx 5$-$10°$).

The amplitude of the velocity roughly follows an exponential

$$v(h)=v(0)e^{h/H_0} \tag{12}$$

according to Koch et al. (1979) with $v(0)=280ms^{-1}$ and the scale height $H_0=900Km$. The density scale height for comparison is of the order $150Km$. The amplitude of the intensity (temperature?) variation is found to increase very much as function of altitude. It is difficult to observe the oscillations at low levels, but the amplitudes get very high in the line cores and other regions of the spectrum, where the opacity is large. This was noted very early and explained by the short relaxation time in the photosphere, which is only half the truth. Brown and Harrison (1980) has been able to see oscillations in continuum light, but the solar 'noise' dominates. The wing of the NaI D line (Tanenbaum et al.,1969) shows an amplitude of 0.5%, but if you care to go to the infrared, where the opacity is higher, amplitudes as high as 7% have been seen (Noyes and Hall,1972).

The phaselag of the blueshift to intensity has been studied by several authors. At P=300 s values for the wings of lines tend to give a value <90° (Tanenbaum et al.,1969 and Sivaraman,1973), but for a weak C line Deubner (1974) get a value as small as 40°. At shorter periods Deubner in FeI sees a phaselag of 130°. In the line core most agree on an adiabatic value of 90° (Tanenbaum et al.,1969, Deubner,1974, Mein,1977, Cram,1978). An exception is found by White and Athay (1979) for the UV SII line, where the result is 60°.

The early results are summarized in Table I.

TABLE I: EARLY RESULTS

Type of data	Result	Reference
Intensity ampl.	Wing of NaI $\Delta I \approx 0.5\%$ CO lines 4.67μ $\Delta I \approx 7\%$	Tanenbaum et al.(1969) Noyes & Hall(1972)
Velocity ampl.	$V(h)=V(0)e^{h/H_0}$, $V(0)\approx 280m/s$, H_0=900Km	Koch et al.(1979)
Phaselag vel.-vel.	most linepairs $\Delta\varphi<5°$ $\varphi(NaI)-\varphi(H\alpha)\approx 15°$ $\varphi(TiI)-\varphi(MgI)\approx 10°$	Deubner(1974) Deubner(1974) Evans & Michard(1962)
Phaselag Int.-vel.	Core of lines: $\varphi_I-\varphi_v \approx 90°$	Mein(1977), Cram(1978) Deubner(1974), Tanenbaum et al.(1969)
	Wings of lines: $\varphi_I-\varphi_v<90°$	Tanenbaum et al.(1969), Sivaraman(1973)
	UV lines: $\Delta\varphi\approx 60°$	White & Athay(1979)

The later observations deserve to be shown in more detail, because a single number do not give justice to the wealth of information contained in many of the diagrams presented. The following figures give a taste of what observers have produced.

Schmieder (1979) studied the MgI 5172.7 line and measured velocity and intensity for different positions in the line profile. Fig. 4 attach numbers to points in the profile. Fig. 5 illustrate, that the velocity amplitude increases with height The increase is less pronounced than (12) suggests. Schmieder also gives a v-v phase lag diagram, which shows that in the evanescent region pairs of velocities are in phase within 5°. Fig. 6 is more interesting and plots the delay of the maximum blueshift relative to maximum intensity for four points in the profile. For a given point the phaselag is nearly constant through the evanescent region, but going from the line core '12' to the near line wing '9' the phaselag increases from around 90° to 130°. The next paper of the same type is by Lites and Chipman (1979). They have measured many phase relations between the velocities and intensities in the center of *different* lines: FeI, MgI and CaII, which correspond roughly to a

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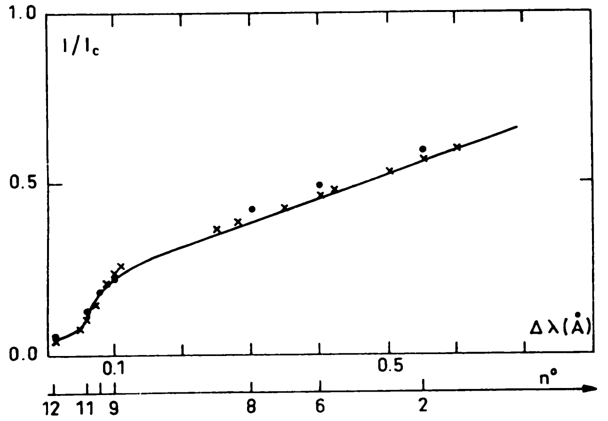

Fig. 4. The MgI 5172.7 line with the numbers labeling points in the profile. (Schmieder,1979)

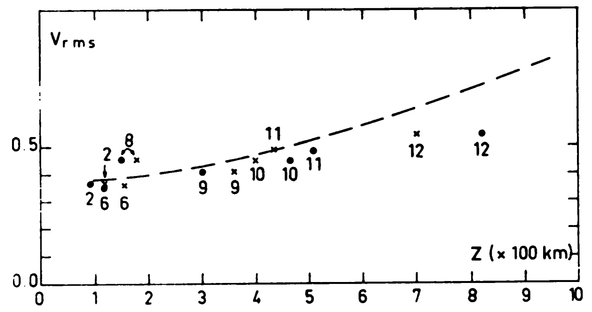

Fig. 5. The velocity amplitude at different positions in the line profile mapped onto the height using contribution functions. (Schmieder,1979)

photospheric, a low chromospheric and a chromospheric line. Fig. 7 is the same story once more: no big change of phase among velocities for low lying lines. The CaII line velocity shows a phase, which begins to deviate from the lines formed at lower levels. Turning to the same type of diagram as Fig. 6, there seem to be some discrepancy among Lites and Chipman and the other authors. Looking at Fig. 8 one first notices, that it is the delay of intensity to blueshift, that has been plotted, and that one then will get negative numbers for evanescent waves. But if one turns the figure upside down it becomes clear, that the phaselag in the Fe I line is below 90°. The Ca II phaselag on the contrary stays above 90°. Perhaps the FeI observations plotted in Fig. 8 refer to a different formation height. Staiger et al.(1984) provide some of the latest results seen in Fig. 9. They seem to get results

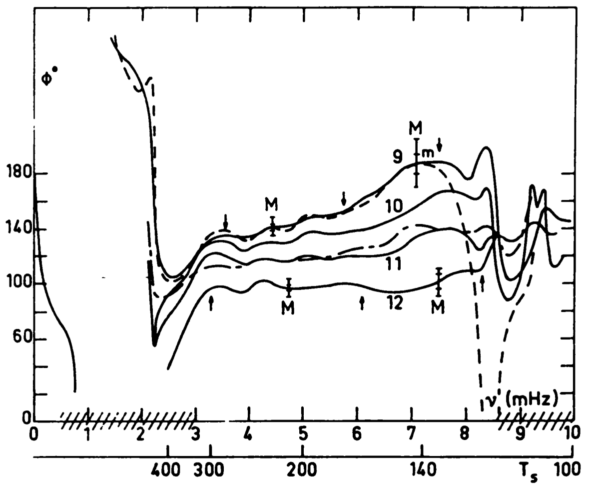

Fig. 6. Phaselag $\varphi(I/v)$. Error bars are indicated. The point '12' is the line center, '9' the wing at the edge of the core. The data above the hatched part of the x-axis are unreliable. (Schmieder,1979)

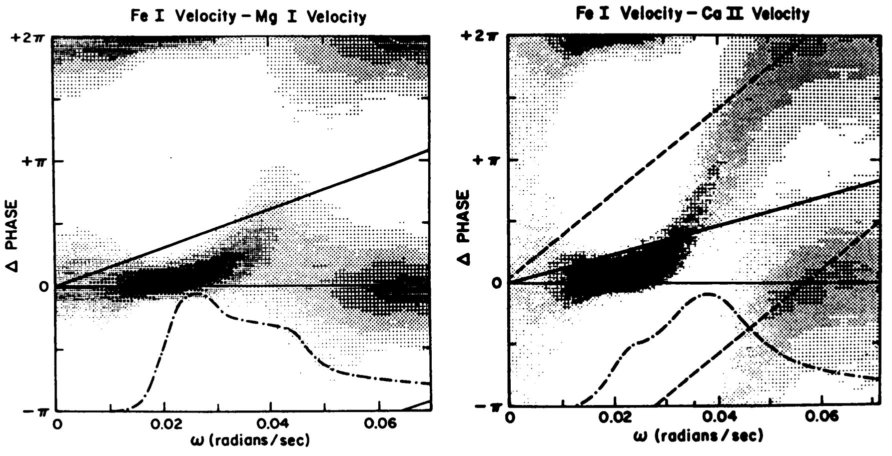

Fig. 7. Velocity phase differences for pairs of lines. The straight line corresponds to the phase difference for a traveling wave with the the photospheric sound speed. (Lites and Chipman,1979)

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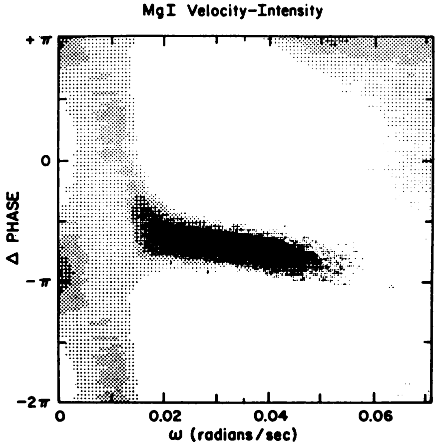

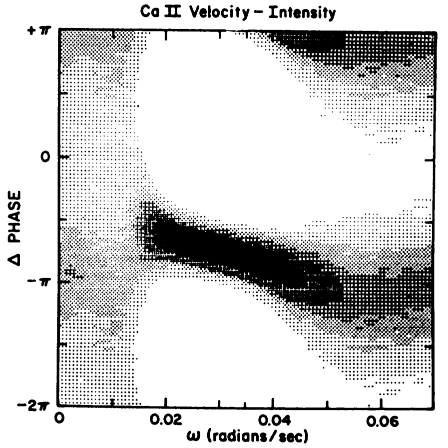

Fig. 8. Velocity - Intensity phaselags. (Lites and Chipman,1979)

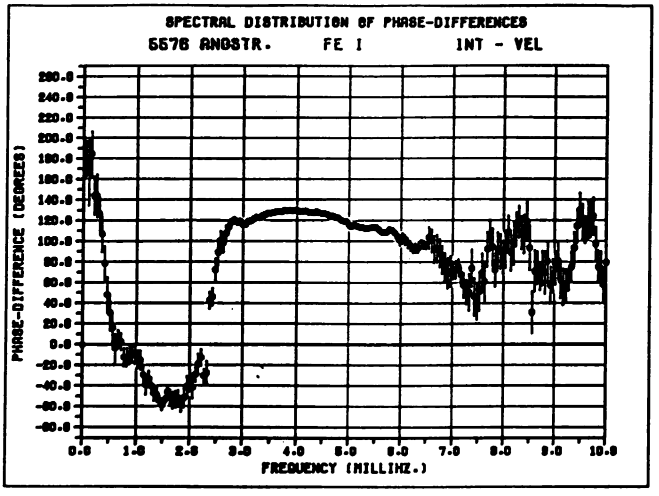

Fig. 9. There are 3 different regions: $\nu < 2.5mHz$ where signs of gravity waves are visible (negative phases), $2.5mHz < \nu < 6mHz$ give the phases of p-modes and $6mHz < \nu$ is the traveling wave domain. (Staiger et al.,1984)

consistent with Schmieder, but with less noise. They have measured a number of different lines, but it is not possible to show more than one figure here.

A slightly different representation is Fig. 10 due to Andersen (1984). The amplitude of the relative intensity variation is plotted as function of position in the line profile for the FeI 5576 line. The increase towards the center of the line indicate, that the temperature fluctuations are very roughly 5 times higher in the low chromosphere than in the continuum forming layers. The total collection of results put severe restrictions on the solar atmosphere model and also on the precise treatment of the linear waves in the model. It is at present impossible, as you will see in the next section, to match accurately all the phases with a single model.

To round off this section a few remarks about chromospheric oscillations. The small cavity in the chromosphere is coupled to the photosphere through the evanescent region. It is unlikely that oscillations are self-excited in the chromospheric cavity, but it can resonate with modes of the right frequency leaking through from the photosphere. Recent observations by Deming et al. (1986) strongly suggest that this is the case, but also Kneer and Uexhüll (1983) find weak ridges or power at a period $P \approx 180s$. The ridges are horizontal, because the period is the same for all horizontal wavenumber k_h. One might observe different frequencies from time to time or from place to

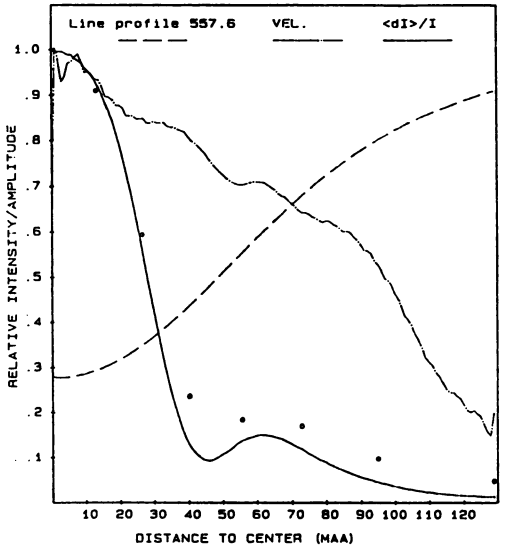

Fig. 10. Amplitudes of velocity and intensity in a spectral line. The result is an average over the p-mode region of the spectrum. Circles are calculated values by Frandsen (1984). The bump at 60 mÅ is real and not due to asymmetries in the line profile. (Andersen,1984)

place, because the chromosphere is very inhomogeneous, so that the extent of the cavity can change.

5. INTERPRETATION OF THE OBSERVATIONS.

Can we explain the facts in a simple way? The answer is no, but to some extent simple arguments work quite well. The problem can be divided into the following logical steps:

1. Determine the mean height of formation for the feature, that is being observed (Mein and Mein,1980, Lites and Chipman,1979, Schmieder,1979, Frandsen,1984).
2. Compute the radiative cooling time at the height just derived (Canfield,1974, Giovanelli,1978).
3. Consult the tables or figures for the isothermal atmosphere (with T equal to the local temperature) and get the phaselag or whatever quantity is being sought.

If the computed quantities agree well with the observables one would say, that "we understand" the observations. Applying this technique to the results described in the previous section turns out to be quite successful in some directions and utterly fails in other. The amplitudes of the velocity and the intensity in the photosphere increase outward as explained earlier, but in the chromospheric layers the intensity and thus the temperature amplitude become more difficult to analyze. The intensity fluctuations are small in the photosphere as expected due to the high dissipation, which tends to make the oscillation isothermal. The phases of velocities derived from different lines or from different points in a single line should not deviate very much from each other, which is really the case, except for strong lines. For progressing waves the phase change correspond reasonably well to the acoustic travel time between the line forming layers.

The phaselag of blueshift to intensity is expected to be close to or slightly above 90° depending on the amount of radiative damping. Values around 120° are observed in the cores of photospheric lines confirming the expectations, but at lower and at higher altitudes the isothermal model does not work well. At continuum optical depth unity the phaselag is much smaller than 90°.

The phases of traveling waves have been discussed in much detail by Deubner et al. (1984). When the wavelength becomes comparable to the thickness of the line forming region phases change very quickly. He also points out the 'phase pull' from noise sources like seeing or solar granulation.

Now the whole atmosphere can not be treated as a set of isothermal regions. Radiation couple every part of the atmosphere with all other parts. A feasible improvement is to compute the detailed behaviour of the waves as function of height from the hydrodynamical equations.

Schmieder (1977) published such computations based on the HSRA model. Later calculations were carried out by Christensen-Dalsgaard and Frandsen (1984) on an improved model of the Sun, the VAL model, with a more complete treatment of the radiation field. Also Hill et al (1978) have studied the effects of the non-local character of the radiation field in a real atmosphere, which takes away some of the usefulness of a relaxation time. In fact you can get a negative relaxation time, which of course reflect, that the wave is driven in that area and not damped.

A quantitative comparison is now possible between computed and observed parameters and amplitudes and phases agree generally within the accuracy of the observations, but there are difficulties. The phaselag *I-v* in Fig. 6 of Schmieder (1977) and in Fig. 11 from Frandsen (1985) behaves differently. Where I get a curve with a maximum around the temperature minimum, Schmieder obtains a minimum with values less than 90° at $\log\tau_{5000}$=1. The observed values in Fig. 11 agree for the temperature minimum region, but at the bottom of the atmosphere large discrepancies show up. Let us look a little closer at the problem. The intensity perturbation at the surface is computed from a perturbed source function of the type

$$\delta S=\delta S_0-\frac{\delta\kappa}{\kappa}(I-S) \tag{13}$$

by integrating over the optical depth

$$\delta I=\int\delta S e^{-\tau}d\tau \tag{14}$$

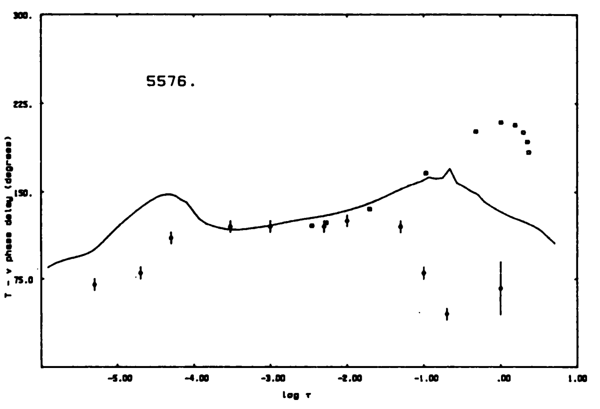

Fig. 11. The phaselag I-v and T-v. The full drawn curve is the phase of $\delta T/T$ from a model calculation; squares are the $\delta I/I$ phase from the same model, and circles are observed phases with estimated error bars.

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The δS_0 is the direct perturbation of the source function (in LTE the Planckfunction B_ν). δS_0 is then proportional to the temperature perturbation δT and has the same phase. If the temperature or pressure terms dominate in $\delta\kappa$ ($\frac{\delta\kappa}{\kappa}=\kappa_T\frac{\delta T}{T}+\kappa_P\frac{\delta P}{P}$), then there is a chance that δS is dominated by the second term in equation (13) and has a phase considerably different from δT. As the integration in (14) produces an average phase, it can be very hard to assign the observed phase to any depth, and it can be difficult to compute an accurate phase, because it depends on the opacity derivatives κ_T and κ_P, which are not well determined physical parameters.

This is all true even for the simple case of a radial mode. All the horrible effects an average over a non-radial mode can bring about, when one tries to interpret an observed phase, are dramatically described in a paper by Mihalas (1984). I refer to this paper, if anybody think that the diagnostics of p-modes in an atmosphere is a trivial matter.

At the end of this section a few remarks should be added about observations of the solar limb. The response at the limb to the oscillations is really a tough problem. Due to the large rise of the temperature perturbations in the upper layers, the amplitude of the intensity variation will increase quickly towards the limb and then make a fast drop when you pass the limb. One has to worry about the horizontal component of the velocity even if it is small, due to the projection of the vertical velocity, which vanishes at the limb itself. The rays passes through a large part of the upper atmosphere where the atmosphere is inhomogeneous and the models uncertain. Thus limb darkening measurements are as difficult to interpret as to perform, which has been realized by Hill et al. (1986).

6. INVERSION.

As models fail to produce results that fit all observations, one could try to calculate corrections to the the model. The first attempt could be to correct the eigenfunctions , so that the observations of spectral lines and continuum fluctuations were reproduced. There is not complete freedom to do anything to the eigenfunctions, but some of the neglected physics in the computations of the eigenfunctions can be simulated by appropriate analytical terms with a limited number of free parameters. If wisely chosen the free parameters can be determined by fitting the data, and the eigenfunction computed with this fit. To go beyond that and change the model of the solar atmosphere and envelope will be difficult, because there are many unknown steps from a model to the eigenfunctions one can calculate. On the other hand it might turn out, that it is impossible to reproduce the observations fiddling the eigenfunctions so that one has to change the initial assumptions. Such semi-empirical eigenfunctions represent an approximation to the actual waves and might be used as boundary values for the computation of the global eigenfunctions. Also one might try to trace back the reason for the needed corrections and locate the physical mechanism, that has been missing in the model calculations.

REFERENCES.

Andersen,B.N. 1984, *Proc. of the 25th Liège Int. Astron. Coll.,(Eds. Noels & Gabriel)*, 220

Brown,T.M. and Harrison,R.L. 1980, *Astrophys.J.* **236**,L169

Brown,T.M. 1984, *Science* **226**,687

Brown,T.M., Mihalas,B.W., and Rhodes Jr.,E.J. 1985, *Physics of the Sun I,(Ed. Sturrock),Reidel*,177

Canfield,R.C. 1974, *Astrophys.J.* **194**,483

Christensen-Dalsgaard,J. and Frandsen,S.F. 1984, *Mem.Soc.Astron.Ital.* **55**,285

Cram,L.E. 1978, *Astron.Astrophys.* **70**,345

Deming,D., Glenar,D.A., Kaufl,H.U., Hill,A.A. and Espenach,F. 1986, *Nature*,(to be published)

Deubner,F.L. 1974, *Solar Phys.* **39**,31

Deubner,F.L., Endler,F. and Staiger,J. 1984, *Mem.Soc.Astron.Ital.* **55**,135

Durney,B.R. 1984, *Solar Seismology from Space, Snowmass (JPL publication 84-84)*,325

Evans,J.W. and Michard,R. 1962, *Astrophys.J.* **136**,493

Frandsen,S. 1985, *Seismology of the Sun and the distant Stars,(ed. Gough),Reidel*,73

Giovanelli,R.G. 1978, *Solar Phys.* **59**,293

Hill,H.A., Rosenwald,R.D. and Caudell,T.P. 1978, *Astrophys.J.* **225**,304

Hill,H.A., Task,J. and Padig,C. 1986, *Astrophys.J.* **304**,560

Kneer,F.J. and Uexhüll,M. 1983, *AstronAstroph.* **119**,124

Koch,A., Küveler,G. and Schröter,E.H. 1979, *Solar Phys.* **64**,13

Lites,B.W. and Chipman,E.G. 1979, *Astrophys.J.* **231**,570

Mein,N. 1977, *Solar Phys.* **52**,283

Mein,N. and Mein,P. 1980, *Astron.Astroph.* **84**,96

Mihalas,B.W. 1984, *Small-scale dynamical processes in quiet Stellar Atmospheres, Sunspot 1983,(Ed. Keil)*,235

Nordlund,A. 1984, *Small-scale dynamical processes in quiet Stellar Atmospheres, Sunspot 1983,(Ed. Keil)*,181

Noyes,R.W. and Leighton,R.B. 1963, *Astrophys.J.* **138**,631

Noyes,R.W. and Hall,D.N.B. 1972, *Astrophys.J.* **176**,L89

Schmieder,B. 1977, *Solar Phys.* **54**,269

Schmieder,B. 1979, *Astron.Astroph.* **74**,273

Sivaraman,K.R. 1973, *Solar Phys.* **33**,333

Souffrin,P. 1966, *Ann.Astroph.* **29**,55

Souffrin,P. 1972, *Astron.Astrophys.* **17**,458

Staiger,J., Schmieder,B., Deubner,F.L. and Mattig,W. 1984, *Mem.Soc.Astron.Ital.* **55**,147

Stein,R.F. and Spiegel,E.A. 1967, *Journ.Acoust.Soc.Amer.* **42**,866

Tanenbaum,A.S., Wilcox,J.M., Frazier,E.N., Howard,R.F. 1969, *Solar Phys.* **9**,328

White,O.R. and Athay,R.G. 1979, *Astrophys.J.Suppl.* **39**,347

Zhugzhda,Y.D. 1983, *Sovjet Astron.Lett.* **9**,329