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Velocity and intensity oscillations in sunspot penumbrae

M. Sigwarth and W. Mattig

Kiepenheuer-Institut für Sonnenphysik, Schöneckstrasse 6, D-79104 Freiburg i. Br., Germany

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Abstract. Velocity and intensity oscillations in the penumbra of a sunspot close to disc center are investigated at various atmospheric heights from the photosphere to the upper chromosphere using simultaneous time series of spectra of FeI 5123 Å, Mg b1, Na D1/D2, NiI 5893 Å, Hα and CaII 8542 Å. Line core shifts and intensity variations are determined for all positions along the slit and power, coherence and phase spectra are calculated.

Both Doppler velocities and line core intensity fluctuations are significantly reduced inside the penumbra and the surrounding plage region in all atmospheric layers compared to the surrounding quiet sun. Inside the penumbra the velocity oscillations are found to be coherent over a larger spatial range in photospheric and middle chromospheric layers than outside.

Velocity power spectra show the 5-minute oscillations up to lower chromospheric levels from the inner to outer penumbra boundary. Only in the layer below the temperature minimum the 5-minute oscillations are not detectable in the inner and central penumbra.

In the upper chromosphere frequencies significantly changes from 6 mHz at the inner penumbra to around 1.5 mHz at the outer penumbra boundary.

Intensity oscillations show power at low frequencies ($\leq$ 2 mHz) outside the spot and in the outer penumbra in all atmospheric layers while in the central penumbra power in the 5-minute range is present only in the layer below the temperature minimum.

From a coherence and phase analysis we find upward propagating waves inside the penumbra with a different behavior in deeper and higher layers and compared to the quiet sun.

No differences could be found for the oscillatory behavior in dark and bright penumbral filaments (at a mean spatial resolution of 1 arcsec).

Key words: Sunspots – oscillations – photosphere – chromosphere

1. Introduction

A recent review of observations and theoretical models of chromospheric penumbral oscillations is given by Lites (1992). A complete review of observations of penumbral oscillations in photospheric layers as well as existing theoretical models and explanations is given by Marco et al. (1996).

It is still not clear whether penumbral oscillations in different heights are of the same origin and are only affected by the penumbral structure in different heights or if they are excited by several mechanisms, such as umbral oscillations, photospheric 5-minute oscillations, and convection. Also it is not clear, how the oscillations inside the penumbra are influenced by the penumbral fine structure, (i.e. the magnetic field structure) and the Evershed effect. To bring more light on these questions, simultaneous observations from deeper layers up to the chromosphere with high spatial resolution are necessary.

In the present paper we investigate velocity and intensity oscillations simultaneously in the penumbra and surrounding quiet sun from photospheric to upper chromospheric layers. We are looking for spatial changes of the oscillatory behavior and investigate the vertical propagation characteristics in the penumbra at the different atmospheric heights and compare these results with the oscillations outside the spot.

Table 1. Spectral lines, diffraction order m, dispersion D and film types (Kodak).

Lines	FeI	Mg b1	NiI	Na D2/D1	Hα	CaII
λ(Å)	5123	5184	5893	5890/5896	6563	8542
m	44	43	38	38	34	27
D(mm Å^{-1})	9.5	8.7	7.9	7.9	6.9	5.1
Film	2476	103a-G	2498	2498	2476	2581

2. Observations

The observations were carried out by one of us (W. M.) at October 18, 1982, with the Vacuum Tower Telescope at Sacramento Peak Observatory, Sunspot, New Mexico. Using the Echelle spectrograph time series of spectra of photospheric and chromospheric lines were simultaneously recorded photographically. Table 1 contains the spectral lines, the diffraction order in which the lines were observed, the resulting dispersion and the film types used for recording the different spectral bands.

By placing the slit alternately at two different positions in the penumbra of a roughly regular sunspot near disk center, we obtained two time sequences for each spectral line. Each sequence consists of 110 spectra (except the Hα series, which ended after

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Send offprint requests to: M. Sigwarth

Table 2. Observational data

Date:	October 18, 1982
Spot:	NOAA# 3950 ($\cos\theta = 0.98$)
Time:	17.35–18.30 UT
Δt:	30 s (for each slit position)
Exposure time:	4 s
Slit width:	200 μm ($\widehat{=}$ 0.7 arcsec)
Slit length:	62 mm ($\widehat{=}$ 230 arcsec)
Slit position P1:	S 7.4, W 0.1
Slit position P2:	S 6.4, E 1.2

93 spectra) with a time difference Δt of 30 s and therefore a total duration of 55 min. At position 1 (P1) the slit covered the central part of an undisturbed penumbra perpendicular to the filamentary structures, while at position 2 (P2) a more irregular penumbra near the border of umbra and penumbra was covered. So we concentrate our presentation to the results gained from P1 as a more typical penumbra. In each position the slit also covered parts of the surrounding photosphere.

Fig. 1 shows white light slit jaw images of the two position. (Slit jaw images taken in CaII K were also available.) More observational details are listed in Table 2.

3. Data reduction

The photographic spectra were digitized with the microdensitometer of the Kiepenheuer-Institut. The scanning aperture (and step width) were 110 x 110 μm^2 corresponding to 0.37 arcsec in spatial direction and between 12 and 21 mÅ in dispersion. By means of the characteristic curves the film densities were transformed into intensities.

Linear wavelength shifts were taken into account and subtracted. Shifts in slit direction of successive spectra were corrected by cross correlating the intensity profiles along the slit.

Line core positions and intensities for each spatial position were determined by calculating the minimum of quadratic polynomials fitted to the line cores. To avoid influences of asymmetries from line wings, we restricted the fits to a few points around the intensity minimum depending on the FWHM and spectral resolution of each line. From line core shifts relative to the temporal mean line core position Doppler velocities were calculated. Line core intensity variations were determined relative to the local continuum intensity, i.e. we determine the line core intensity variations relative to the deepest layers visible in the penumbra and quiet sun.

Seeing conditions for nearly the whole series were good and fairly stable. For the best single spectra the spatial resolution is about 0.4 arcsec, the mean resolution for the whole analyzed series is about 1 arcsec.

Power, coherence, and phase spectra were computed using an FFT-routine based on an application of Edmonds & Webb (1972). The data sets were apodized with 10% cosine windows and slightly smoothed by averaging over each three neighboring data points. No filter was applied to the data. The Nyquist frequency resulting from the cycle time of 30 s was 16.7 mHz, and the frequency resolution for the whole series was 0.3 mHz (0.36 mHz for the shorter Hα series).

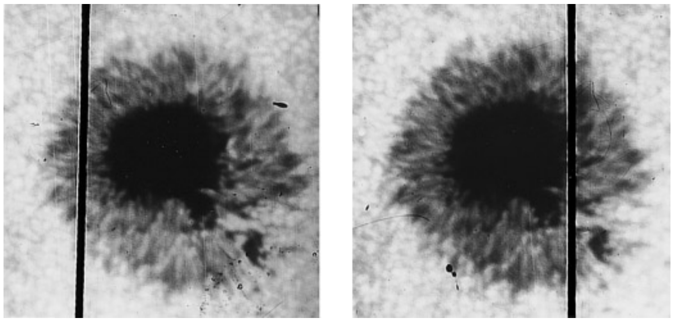

Fig. 1. White light images of slit position P1 (left) and P2 (right)

4. Results

4.1. Atmospheric layers

The formation heights of the investigated line cores cover a wide range from the photosphere to the upper chromosphere. The investigated lines represent the following atmospheric layers:

NiI:	photosphere
FeI:	below temperature minimum, upper photosphere
Mg b1:	around temperature minimum
Na D1/D2:	above temperature minimum, lower chromosphere
CaII/Hα:	upper chromosphere

In the following we use these terms in order to name the different atmospheric heights.

4.2. Doppler velocity and line core intensity variations

The amplitudes of both the temporal intensity (I) and velocity (V) fluctuations are reduced remarkably inside the penumbra at all observed atmospheric layers compared to the surrounding (more or less) undisturbed sun ($\odot$). Table 3 gives a comparison of the spatially averaged V and I rms-values inside and outside the penumbra (at P1) for all observed atmospheric layers.

The mean ratio of the rms–values of all investigated lines from inside and outside the penumbra for P1 are:

$$\bar{V}_{rms}(\text{pen.}) / \bar{V}_{rms}(\odot) = 0.73$$
$$\bar{I}_{rms}(\text{pen.}) / \bar{I}_{rms}(\odot) = 0.89.$$

For P2 the reduction is less strong due to the more disturbed penumbra:

$$\bar{V}_{rms}(\text{pen.}) / \bar{V}_{rms}(\odot) = 0.86$$
$$\bar{I}_{rms}(\text{pen.}) / \bar{I}_{rms}(\odot) = 0.95.$$

Fig. 2 gives an example of the time variation of Doppler shifts and line core intensity fluctuations over the whole spatial range gained from Na D1 (P1). Inside the penumbra velocity and intensity variations (rms-values) are reduced by a third compared to the surrounding undisturbed sun. The spatial range of coherent V oscillations along the slit are larger inside the penumbra than outside and reach up to the size of the

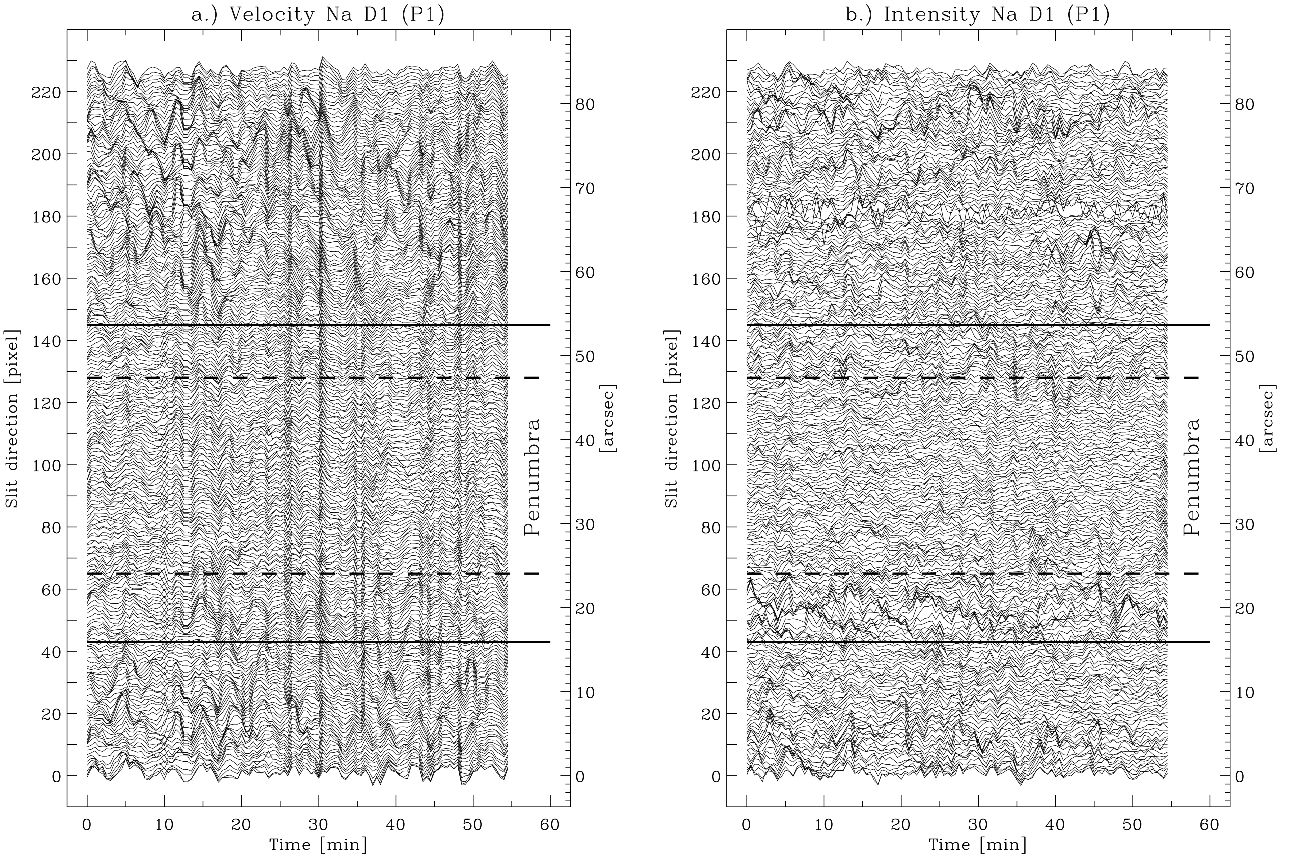

Fig. 2. **a** velocity and **b** intensity fluctuations of Na D1 over the whole spatial range of 84 arcsec for slit position P1 (one pixel corresponds to 0.37 arcsec). The range of the penumbra covered by the slit is shown by the dashed and solid lines (see Fig. 3 for details). Inside the penumbra the amplitudes are reduced to about 35% of the areas outside. The size of coherently oscillating areas is larger for V oscillations. In **a** one can see artificial deflections at t=26, 30, and 48 min which are due to slight mechanical shifts of the Echelle-spectrograph or seeing.

Table 3. Spatially averaged rms-values for Doppler velocity (V_{rms}) and relative line core intensity fluctuations (I_{rms}) in the penumbra (pen.) and surrounding quiet ($\odot$) sun (for slit position P1). The rms-values are averaged along the slit from pixel 70 to 120 (pen.) ($\widehat{=}$ 18.5 arcsec) and from 160 to 220 ($\odot$) ($\widehat{=}$ 22.2 arcsec) (see Fig. 2). The rms-values were calculated from noise-corrected power spectra (by subtracting the noise from the power spectra). The spectral lines are listed according to increasing formation height.

Lines	$V_{rms}(\odot)$ (km s^{-1})	V_{rms}(pen.) (km s^{-1})	$I_{rms}(\odot)$ % of $I_{cont.}$	I_{rms}(pen.) % of $I_{cont.}$
NiI	0.27	0.18	1.52	0.86
FeI	0.34	0.26	0.91	0.60
Mg b1	0.36	0.29	0.42	0.57
Na D1	0.34	0.22	0.24	0.15
Na D2	0.33	0.23	0.19	0.15
CaII	0.47	0.35	1.11	0.74
Hα	0.70	0.51	0.83	0.74

penumbra covered by the slit of about 25 arcsec ($\approx$ 18 000 km). No horizontal wave propagation is visible. This behavior can be observed from photospheric layers (NiI) up to lower chromospheric layers (Na lines). In higher chromospheric layers (CaII, Hα) we find periodic V fluctuations only inside the penumbra whereas irregular and long term variations dominate outside. The chromospheric coherent oscillating areas inside the penumbra are smaller than in deeper layers (up to about 15 arcsec). For P1 we also do not find clear indications for horizontal wave propagation in high layers. But for P2 we find outward moving waves: in the inner part of the penumbra short period fluctuations (3 to 5 minute) with a phase velocity in the range 10 to 40 km s^{-1} and at the outer penumbra border long period fluctuations ($\approx$ 30 minute) with a small phase speed of 2 to 3 km s^{-1}.

The reduction of Doppler velocities in the penumbra is well known. Balthasar et al. (1987) and Balthasar & Wiehr (1989) found a damping of Doppler velocities inside sunspot umbrae and penumbrae in photospheric layers. For penumbral oscillations below the temperature minimum Thomas et al. (1984) also find evidence of phase coherence in the penumbra extending over distances in excess of 30 arcsec.

The spatial variations of line core intensities are in general more irregular than Doppler velocity variations as can be seen in Fig. 2b. Because the amplitudes of the I fluctuations are decreasing to some 0.1% of the continuum intensity (see Table 3) we are operating at the limit of photometric accuracy.

The *height dependence* of rms-values inside and outside the penumbra is the same. The amplitude of V fluctuations (V_{rms}) increase from mid-photospheric layers (NiI) to the chromosphere (Hα) with a stagnation above the temperature minimum. The I rms-values first decrease from photospheric to mid-chromospheric layers (Na D1/D2) and then increase toward higher layers.

4.3. Power spectra

We plotted the power spectra over the whole spatial range as contour plots shown in Fig. 3.

Several V power peaks in the 5-minute range appear as “bands“ along the slit direction inside the penumbra. The power inside the penumbra seems to be more concentrated (or separated) around the main frequencies than outside. This effect is due to the reduced power and therefore smaller width of the power peaks inside the penumbra and is not an effect of a frequency dependent damping inside the penumbra. But the bands indicate the larger spatial coherency of the oscillations inside the penumbra at these atmospheric layers. The reduction of power reach over the visible penumbra boundary (here light grey), specially at the upper boundary, where the slit covers a plage region close to the spot (visible in the Ca K slit jaw images).

The power spectra of the two Na lines are practically identical. This is to be expected because the sodium lines are formed in nearly the same atmospheric layer and thus indicate the accuracy and quality of the power spectra we obtained. The V power spectra of NiI and Na lines both for the penumbra and the surrounding quiet sun are also very well correlated.

The V power spectra of FeI correspond to them only outside and in the outer parts of the penumbra while in the central part of the penumbra the power in the 5-minute range disappears. Enhanced power at low frequencies (around 1 mHz) is present at the central penumbra only for FeI. We split the series and found the same behavior for each subsequence.

In the upper chromospheric layers there is a significant change from low frequencies ($\leq$ 2 mHz) at the penumbra boundary to higher frequencies (3 to 4 mHz) in the inner penumbra. (At P2 V power spectra of CaII and Hα show the same up to 6 mHz.) This confirms similar observations by Beckers & Schultz (1972), Lites (1984) and Marco & Mattig (1994). Outside sunspots low frequency V oscillations in the chromosphere were also found in the network (Lites et al. 1993) and in prominences (Balthasar et al. 1993).

FeI intensity oscillations in the 5-minute range are present in the central penumbra exactly at the same position where the V oscillations around 3 mHz disappear. From the other lines only for Hα I signals are present in the central penumbra. For Hα the I signals are correlated with V signals. In all lines I power is present in the outer penumbra at low frequencies from 1 to 3 mHz.

Our observations show no correlation between penumbral fine structures and oscillatory behavior. We compared power spectra averaged over dark and bright penumbral filaments (visible in the linecore of NiI and FeI) and did not find any significant difference in frequency or amplitude for the V oscillations. But one should take into account, that the size of penumbral fine structures is below the mean spatial resolution of 1 arcsec (750 km) we obtain. From two dimensional spectroscopy with spatial resolution comparable to ours, Balthasar et al. (1996) neither could find a dependence of velocity oscillations in the 5-minute range on the long live filamentary structures of the penumbra in photospheric heights, but they find differences in the 8 to 20 minute range.

4.4. Coherence and phase spectra

We used coherence and phase analysis to investigate the vertical propagation characteristics. Coherence and phase spectra for different line pairs for velocity (V–V) and intensity (I–I) and for I–V for several lines were calculated for the central part of the penumbra and for a region outside the spot. A negative phase difference $\Delta\varphi$ between deeper and upper atmospheric layers indicates upwards propagating waves, no phase difference indicates standing waves.

I–I: From I–I spectra we could not obtain clear results. For most line pairs the coherence and thus the phase scatters over a wide range. Outside the spot no connection can be found between intensity oscillation in photospheric (FeI) and upper chromospheric (CaII, Hα) layers while inside the penumbra, especially close to the umbra (P2), upward propagating intensity fluctuations from below the temperature minimum to the upper chromosphere occur, but only at very few spatial positions.

V–V: Fig. 4 shows V–V coherence and phase spectra of several line pairs plotted for 11 spatial positions $\widehat{=}$ 4 arcsec (pixel 95-105; for details see also Fig. 3) at the central part of penumbra P1.

For the sodium lines we expect no phase difference. From our measurements we obtain a phase difference of $\Delta\varphi \approx 0^\circ$ with a scatter of $\pm 7^\circ$ and a coherence of > 0.95 in the 5-minute range. We refer to these values as the upper limit for the accuracy of our measurements.

From the V–V coherence and phase spectra we find a different behavior of wave propagation in deeper (photospheric) and higher (chromospheric) layers inside the penumbra:

(i) In deeper layers (Ni-Fe, Ni-D2) we find upward propagating waves with $\Delta\varphi$ decreasing with increasing frequency. The scatter of the phases is larger ($\pm 10^\circ$) than for D1-D2 but the slope of the phase spectra is still significant.

(ii) In upper layers (D2-CaII, D2-Hα) we do not find a change of $\Delta\varphi$ with frequency.

Although the coherence for CaII-Hα around 4 mHz is better 0.8 we obtained a large scatter of $\pm 15^\circ$ for the phase over the investigated spatial range (not for the single phase spectra itself). A detailed analysis did not show a clear correlation between the spatial position and phase difference. Outside the penumbra in deeper layers the coherence is larger (> 0.8 from 2 to 6 mHz) and the phase difference $\Delta\varphi \approx 0^\circ$. In the chromosphere (here we are still inside the superpenumbra) the coherence is < 0.8 for all frequencies and $\Delta\varphi \approx 0^\circ$.

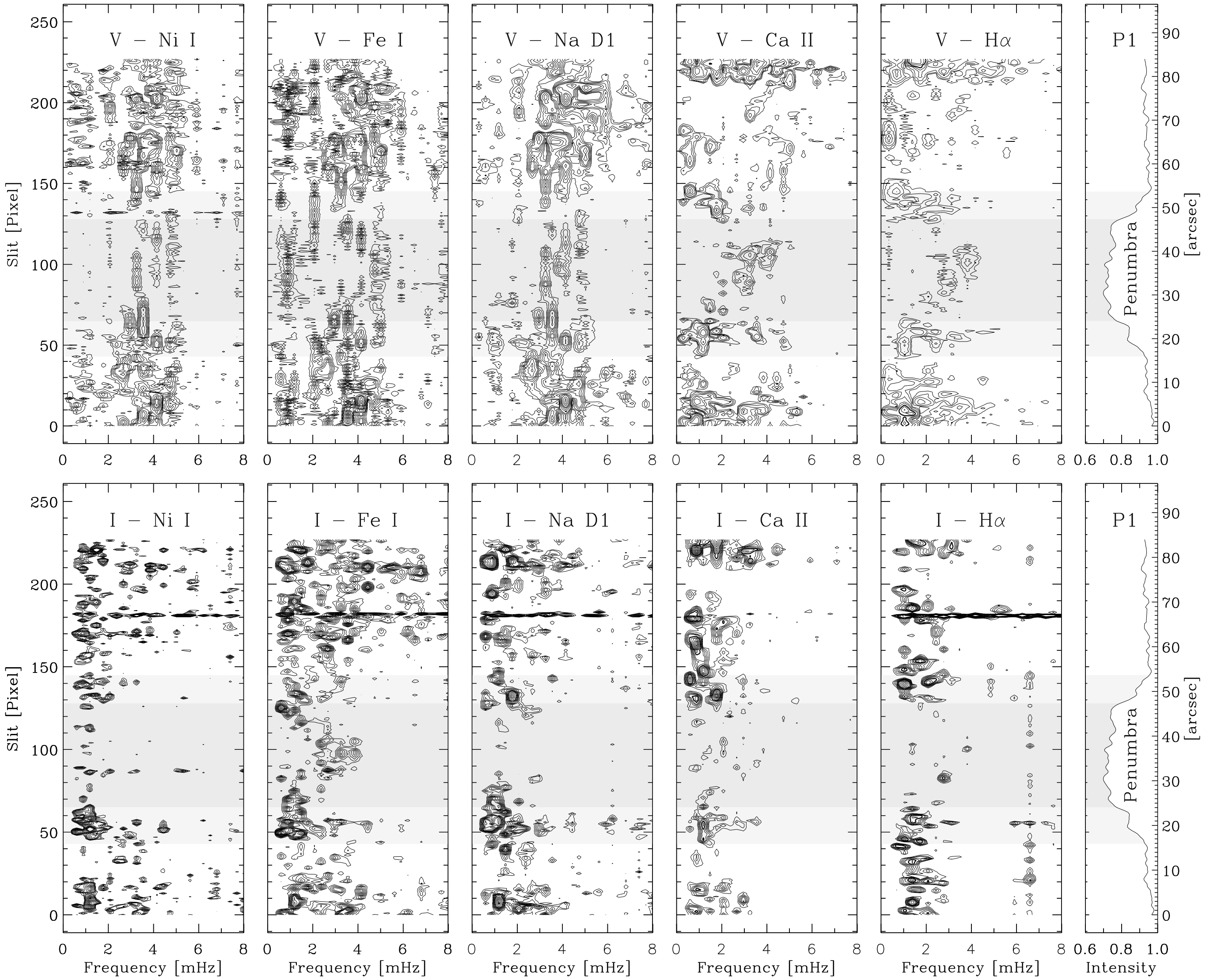

Fig. 3. Power spectra for velocity (upper row) and intensity (lower row) oscillations along the slit direction. The thresholds for the lowest contour levels are according to the 99% significant criterion of Groth (1975). On the right side the continuum intensity along the slit is shown, averaged over all 110 spectra. One pixel in this direction corresponds to 0.37 arcsec. Dark and light grey areas distinguish between the inner part of the penumbra where the mean intensity is constant (apart from the filamentary structures) and the outer region with increasing intensity to the undisturbed sun. The artificial I power values around pixel 180 are due to a hair line at this position.

I–V: Coherence and phase spectra for I–V could be obtained only for the few signals (at specific spatial positions) from the CaII and Hα line in the central (P1) and inner (P2) penumbra between 2 and 4 mHz. Here we found the Doppler velocities leading the intensity fluctuation by a phase difference of about 60° from 2 to 6 mHz.

5. Summary and discussion

The simultaneous observations of the penumbra show the following significant differences in the oscillatory behavior between deeper layers up to the formation height of the Na line cores and upper chromospheric layers:

In deeper layers:

- The presence of 5-minute oscillations in the entire penumbra (except for the higher photosphere, where V power in the 5-minute range is absent in the inner and central penumbra).
- Upward propagating waves with decreasing phase differences to higher frequencies.
- Larger spatial coherence ($\leq$ 25 arcsec, i.e. up to the range of the whole penumbra) of penumbral oscillations compared to the quiet sun and no horizontal wave propagation.

In upper layers:

- A significant change of the frequencies from the central penumbra (4 to 3mHz) to the outer penumbra border (up

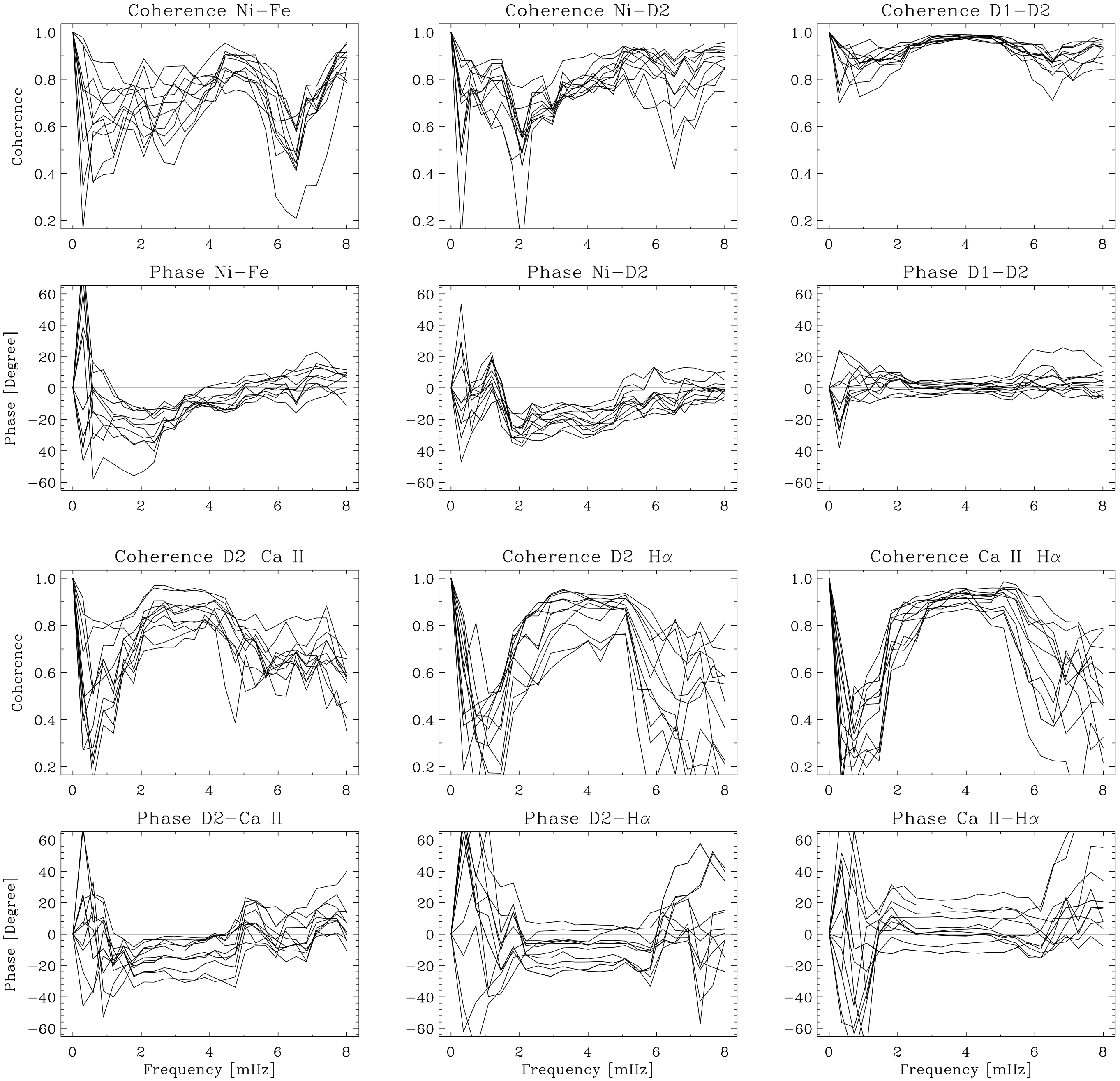

Fig. 4. V–V coherence and phase spectra of various spectral line pairs. Plotted are the spectra for the central part of penumbra P1 (at pixel 95–105 along the slit).

to 2 mHz). At the inner penumbra 3-minute oscillations are present.

- Upward propagating waves with small phase differences which do not change with frequency.
- Smaller spatial coherency ($\leq$ 15 arcsec) compared to deeper penumbral layers.
- Outward moving waves with higher phase velocities (10 to 40 km s^{-1}) in the inner and with small phase velocities (2 to 3 km s^{-1}) in the outer penumbra.

All layers have in common that the Doppler velocities and intensity fluctuations inside the penumbra are reduced. For the inner and central penumbra significant I power in the 5-minute range is present only in the layer below the temperature minimum and for some specific spatial positions in higher chromospheric layers. In the outer penumbra, I power at low frequencies (up to 2 mHz) is present at all observed layers.

The observed differences of the FeI 5123 Å V and I power spectra in the inner and central penumbra compared to those from layers below (NiI 5893 Å) and above (Na D1/D2) are remarkable:

1. Missing V power in the range of 3 to 4 mHz.
2. The presence of low frequency V fluctuations.
3. The presence of I oscillations from 2.5 to 4 mHz.

The appearant long periodic V signal point to an influence of the Evershed effect only in this layer of the penumbra. Rimmele (1995) found evidence that the Evershed effect is located in thin flow channels with a vertical extend of about 100 km. He measured the maximum velocity of the Evershed flow at mid photospheric levels. Below the temperature minimum he found the reversal from the normal to the inverse Evershed effect. Probably the 5-minute oscillations are affected by the Evershed effect in a layer below the temperature minimum where the linecore of the FeI 5123 Å line is formed.

Excitation of the oscillations

We find hints, that the whole penumbra at *photospheric heights* participate in the quite sun 5 minute oscillations:

(a) The similar frequency distribution indicates that there are no specific *penumbral modes*.

(b) The larger spatial coherence of the oscillations inside the penumbra indicate that the penumbra participate as a whole in the photospheric 5-minute oscillations.

The observed oscillations in the *high chromosphere* indicate different exciting mechanisms:

(a) The outward propagating waves in the inner penumbra are possibly excited by umbral oscillations as supported by several other observations (e.g. Lites 1988).

(b) The oscillations in the central penumbra around 3 mHz seem to have their origin from upward propagating waves as the coherence and phase spectra indicate.

(c) The low frequency V oscillations in the outer penumbra are correlated to intensity fluctuations in all observed layers. Evans & Roberts (1990) suggest that these oscillations are driven by granules or overstable convection. Lites (1992) suggest that they are associated with fluctuations in the Evershed effect.

Oscillations and penumbral filaments

In general it is accepted that the oscillatory motions inside the penumbra are aligned with the magnetic field lines in photospheric layers (Balthasar et al. 1987; Balthasar 1990) and in the outer penumbra in chromospheric layers (Lites 1988). Thus, if we accept that bright and dark filaments have different inclination (Beckers & Schröter 1969; Schmidt et al. 1992; Title et al. 1993; Rimmele 1995), our observations should show more V power in the less inclined bright filaments (because our line-of-sight is nearly perpendicular to the solar surface). But we do not observe significant differences between dark and bright filaments. Based on a geometrical model for the average inclination of the magnetic field lines and assuming that these are co-spatial with the filaments, Marco et al. (1996) found, that only in lower photospheric layers the velocity perturbations at the inner and middle penumbra are aligned with the filaments but not in the outer penumbra and in upper photospheric layers. This is in good agreement with our results from direct observations.

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