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The beat of the solar chromosphere's cold heart

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Abstract. The cold heart of the solar chromosphere is best investigated using fundamental band lines of carbon monoxide, CO, at 4.7 μm. We have obtained time series of CO spectra in the quiet sun and in active-region plage at the solar limb and at disk centre. In addition, we have recorded time series in sunspot umbrae located near disk centre. The power spectra and RMS amplitudes of the quiet-sun oscillations at disk centre and at the limb are not compatible with a generally hot chromosphere which is periodically cooled, but support recent suggestions that the low chromosphere is pervasively cool, interspersed with hot, possibly shocked material. In the plage the CO oscillations provide indirect evidence for the expansion of hot material (probably inside magnetic elements) with height. In umbrae the CO lines exhibit well-separated 3 min and 5 min peaks.

We also present spectra of the phase shift between velocity and intensity oscillations of CO lines. At disk centre in the quiet sun the phase shift is on the whole similar to that seen in atomic lines formed near the classical temperature minimum, although with some properties peculiar to CO. In plages the quality of the phase shift is marginal, but suggests either large radiative damping or propagating waves in the 4 mHz frequency range. Finally, in sunspots the phase shift resembles that of atomic chromospheric lines in some umbrae.

Key words: Sun: chromosphere – Sun: oscillations – Sun: infrared – Sunspots – Sun: faculae, plages

1. Introduction

The carbon monoxide or CO molecule is a particularly valuable tool for probing the solar temperature minimum and lower chromosphere. Its vibration-rotation transitions are, firstly, extremely temperature sensitive and, secondly, relatively unaffected by departures from LTE (Ayres & Wiedemann 1989). So far it has mainly been used to investigate the thermal structure of the quiet solar atmosphere (e.g. Noyes & Hall 1972a, b; Ayres 1978, 1981, 1991; Ayres & Testermann 1981; Ayres et al. 1986; Ayres & Brault 1990; Solanki et al. 1994; Uitenbroek et al. 1994; Avrett et al. 1996; Ayres & Rabin 1996), although Ayres et al. (1986), Uitenbroek et al. (1994) and Ayres (1996) have also observed and analysed CO spectra in active regions.

CO vibration-rotation fundamental band transitions at 4.7 μm provide the main evidence for extremely cool gas (cooler than 4000 K) in the solar chromosphere (Noyes & Hall 1972a; Ayres & Testermann 1981; Ayres et al. 1986; Solanki et al. 1994; Avrett 1995; Ayres & Rabin 1996). In radiative equilibrium or in a mildly dynamic atmosphere the same lines can provide the cooling required to reach such temperatures (Ayres 1981; Anderson 1989; Muchmore et al. 1988; Steffen & Muchmore 1988). In a more strongly dynamic atmosphere phases of local adiabatic cooling can supplement and possibly even dominate over the radiative cooling by the CO spectral lines. The two dynamic processes most likely to significantly cool the lower chromosphere are the horizontal expansion of upflowing granular material (or granular overshoot) and solar p-modes or acoustic waves.

The present paper deals with time series of CO vibration-rotation fundamental band spectra of quiet sun, solar active-region plage and sunspot umbrae. It can be considered to be an extension of the work of Noyes & Hall (1972b), Ayres & Brault (1990) and Uitenbroek et al. (1994) in that we not only present and discuss power spectra like the above authors, but also cross-power and phase spectra. Phase diagnostics have been heavily used in the past to identify convective motions, propagating, evanescent and standing waves and to set constraints on damping processes (e.g. Evans et al. 1963; Noyes & Leighton 1963; Edmonds et al. 1965; Mein 1971, 1977; Mein & Mein 1976; Schmieder 1976, 1978; Lites and Chipman 1979; Kneer & von Uexküll 1985; Staiger 1987; Deubner & Fleck 1989; Fleck & Deubner 1989; Keil & Mosman 1989; Deubner et al. 1992, see

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Deubner 1991 for a review). Although handicapped by not having observations of lines formed at widely separated heights we still expect phase diagnostics to be of help in constraining the nature of the oscillations seen in CO. The observations presented here thus provide the basis for testing future models of oscillations and waves in the cool parts of the solar atmosphere.

2. Observations and data analysis

2.1. Observations

The observations were made with the McMath-Pierce facility on Kitt Peak in 1994 and 1995. The vertical spectrograph with the new infrared grating was used in single pass mode together with the InSb single diode Baboquivari detector (Livingston 1991). Quiet sun, active-region plages and sunspot umbrae were observed, with the quiet sun and plages being near both solar disk centre and the solar limb. Close to the solar limb plages can be recognized by their enhanced continuum radiation (faculae); near disk centre the continuum becomes a poor indicator of magnetic flux and we make use of the CO lines themselves. Only regions where these lines are sufficiently weakened are considered to be plages (cf. Sect. 3.3 for details). In addition, the quiet sun was observed at disk centre in double pass mode in order to estimate instrumental degradation of the spectra.

Each region was sampled 128 times at intervals of 30 s, making each time series 64 min long. The 0.5×2.0 mm spectrograph slit was placed parallel to the solar limb when observing close to it.[1] Observations close to the limb were only made under exceptional seeing conditions and with particular care being taken with the guiding. A further test for analysis was that practically no temporal fluctuations be observed in the continuum intensity, suggesting that the proximity of the limb (which in some cases was only a couple of arc-sec away) introduces no artifacts into these data. The depth and wavelength of a telluric line within the observed spectral band were also monitored in order to test for instrumental or terrestrial effects. No significant variations in these parameters were found, except in a few time series which were also not considered for the further analysis.

Three vibration-rotation fundamental band spectral lines of CO at 4.6651 μm (4–3 R23), 4.6657 μm (3–2 R14) and 4.6662 μm (2–1 R6) were recorded. All three lines are similar in strength and are among the strongest unblended CO fundamental band lines.

2.2. Analysis

The central intensity, I (normalized to the local continuum intensity), and the line core wavelength shift relative to the rest wavelength expressed in velocity units, v, were determined for each line in each spectrum. Since the time series and power spectra of the three lines are identical within the limits set by the noise, we add the three v and I time series together, which lowers the noise by a factor of $\sqrt{3}$ without significantly affecting the peaks in the power spectra. Next, power spectra of v and I, their cross-power spectrum, coherence spectrum and $v - I$ phase difference spectrum ($\Delta\phi$) are determined for each time series using the fast Fourier transform and a routine based on the paper by Edmonds & Webb (1972). Long-term trends were removed by subtracting a polynomial fit from the time series and a cosine window was employed for apodization purposes. Finally, the power and related spectra were smoothed with a 3 point running mean. RMS values of I were also calculated, as well as the uncertainties in the power spectra. We provide 99% confidence limits. Above these limits the probability that the signal is not due to noise is greater than 99%. The probability is 99% when the signal is 7.8 times larger than the noise (Groth 1975). We determine the noise from the power spectrum at frequencies above 12 mHz, at which no significant solar signal is expected.

At disk centre the time averaged line core intensity of the 4.6657 μm line corresponds to an excitation temperature of 4460 K for the single pass observations and 4290 K for the double pass observations, values consistent with the traditional temperature minimum (we obtained the temperature values from an application of the Planck function to the line minimum intensities). The difference between the two values is due to the better spectral resolution and absence of stray light in the double pass mode. Interestingly, however, the depth of this line according to Geller (1992) in the data obtained with the ATMOS instrument (Farmer & Norton 1989) corresponds to a temperature of 4390 K, i.e. a value 100 K *larger* than our double-pass observations; partly, we expect, due to weak telluric absorption at the wavelength of this line.[2] This interpretation is supported by the slightly reduced "continuum" level in our spectra relative to the ATMOS data. The 4.6662 μm line, which is affected more strongly by the telluric absorption feature at 4.6667 μm, is deeper in our spectra (excitation temperature approximately 4230 K in double pass) than the 4.6657 μm line, whereas the opposite is the case in the ATMOS spectrum. Nevertheless, we were fortunate in that most of our observations were made under relatively dry conditions; e.g. the rest intensity of the telluric line at 4.6667 μm was greater than 0.8.

We have decided to conservatively correct all (single pass) excitation temperatures derived in this paper in a simple and crude manner by subtracting 70 K from each, corresponding to the difference between the single pass and the ATMOS data. Note that the main effect of spectral smearing with regard to the oscillations is that it mixes the light from nearby wavelengths with each other, which may affect the height in the atmosphere which that wavelength samples. In particular the line core samples somewhat deeper layers than it nominally would.

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[1] The small slit length should be kept in mind when considering $v - I$ phase spectra, since these can depend on wavenumber and location on the sun (in addition to their dependence on $\cos\theta$).

[2] Compare, however, the NSO FTS spectrum with the ATMOS spectrum in Fig. 1 of Ayres 1996, which suggests that the ATMOS data are also somewhat spectrally degraded.

Table 1. Summary of data set parameters and some results

Feature	Location	No. of observations	Mean T (K)	Mean RMS of T (K)	Figure No.
Quiet sun	disk centre	15	4390	50	1
Quiet sun	limb	3	3790	30	2
Plage	disk centre	12	4720	$\lesssim 20$	3
Plage	limb	2	4700	30	4
Umbra	disk centre	14	3300	35	5,6

This should be kept in mind when considering the following results.

3. Results

Table 1 provides a summary of selected time-averaged parameters of the different observed solar features. It lists the type of the observed feature, its location on the solar disk, the number of time series we average together, the mean excitation temperature T of the line core, the mean RMS of the temperature fluctuations and the number of the figure in which the corresponding power and phase spectra are plotted.

3.1. Quiet sun: disk centre

Fig. 1a shows the I and v power spectra averaged over the 15 best quiet-sun time series obtained at disk centre. In Fig. 1b the spectrum of the phase difference between v and I is plotted, together with the spectrum of the coherence of these two quantities. The parts of the power spectra above the horizontal lines are significant at the 99% confidence level (Groth 1975). The frequency interval in which $v - I$ cross-power is significant at the 99% level is indicated in Fig. 1b by the horizontal bar.

The v power is concentrated in the 5 min range (peaking at 3.5 mHz), while I shows significant power between 2.3 and 5.5 minutes (3–7mHz), confirming the behaviour found by Ayres & Brault (1990), Uitenbroek et al. (1994) and, to a certain extent that found for the OH molecule by Deming et al. (1986). Thus v reacts only to photospheric velocities, while I sees both photospheric and chromospheric oscillations. Uitenbroek et al. (1994) explain this behaviour by the increasing radiative damping time with height, so that temperature fluctuations are restricted to greater heights, where the amplitude ratio of the 3 min to the 5 min oscillations is larger than at lower layers. An alternative explanation (proposed by T. Ayres, private communication) is that the velocity, determined from the wavelength of the minimum of a polynomial fit through the lowest part of the line profile, is most strongly influenced by shifts of the inner line flanks, whereas the intensity variations are dominated much more strongly by the actual line core. Hence, according to this explanation the oscillations in I are only seemingly produced higher in the atmosphere than oscillations in v.

The RMS fluctuations in I correspond to an RMS fluctuation of temperature T of approximately 50 K at $\mu = 1$, although individual peak-to-peak fluctuations may be much larger.

The coherence between I and v is considered significant (which is commonly taken to be the case when its value exceeds 0.6), for frequencies between roughly 2 and 10 mHz. The cross-power is also significant at the 99% level between roughly 2 and 8 mHz. The $v - I$ phase difference is negative throughout this range and lies between $-70°$ and $-100°$, although it appears to reach $-30°$ at frequency $\nu = 2$ mHz. Near $\nu = 0$ the $\Delta\phi$ tends towards 0 in agreement with the behaviour of low and mid photospheric lines (e.g. Deubner et al. 1992, i.e., bright material moving towards the observer), whereas lines formed around the temperature minimum level typically show $\Delta\phi \approx 180°$ at low frequencies. The $\Delta\phi(\nu)$ dependence for $\nu \gtrsim 3$ mHz lies between that of Fe I 5576 Å (less negative $\Delta\phi$ than the CO lines) and that of Mg I 5173 Å (which shows a more negative $\Delta\phi$; Lites & Chipman 1979; Lites et al. 1982a) and appears rather similar to that observed by, e.g., Fleck & Deubner (1989) for Na I 5896 Å at $\mu = 1$. Thus the 5 min and 3 min bands show a behaviour consistent with a formation around the classical temperature minimum and even greater heights cannot be ruled out by this diagnostic. The phase spectrum at low frequencies, however, is more similar to those of lines formed in the low photosphere.

This peculiarity begs an explanation. It may have to do with the special properties of these lines, e.g. their extreme temperature sensitivity, or the larger formation height of the continuum at 4.7 μm, so that the intensity fluctuations due to the granulation are different at these wavelengths than in the visible. The oscillations and waves present in the cool CO clouds may also differ from those in the hot part of the chromosphere.

The time-averaged line depth combined with the power and phase spectra suggest a formation near the classical temperature minimum level.

3.2. Quiet sun: limb

Observations near the limb ($\mu = \cos\theta < 0.1$; θ is the heliocentric angle) give a lower time-averaged line-core brightness temperature of 3790 K (after correcting for instrumental influences as described in Sect. 2.2), in good agreement with previous observations (Ayres et al. 1986). From detailed modelling of limb observations Solanki et al. (1994) found that the true temperature of the cool component in which the CO lines are mainly formed lies in the range of 3000–3600 K.

Power spectra of v and I obtained near the limb are plotted in Fig. 2. Each is averaged over 3 observations at $\mu = \cos\theta =$ 0.07, 0.07 and 0.09. Little power (1–2 orders of magnitude less than at disk centre) is visible in the velocity, as expected for the vertically oriented p-modes. Of the slight remaining power in the velocity, there appears to be more at higher frequencies than at disk centre, although the significance of this effect is marginal.

The oscillations are still very much visible in the I power spectrum, although their power is reduced relative to $\mu = 1$ by roughly a factor of 3. The power in I is definitely shifted towards higher frequencies relative to disk centre in the sense that the 3 min peak is now stronger than the 5 min peak, so that

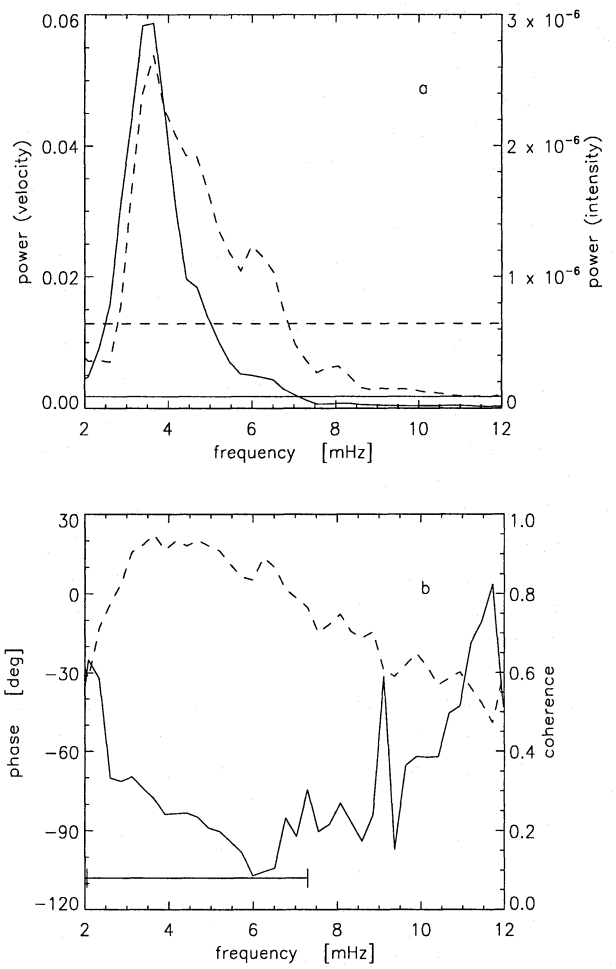

Fig. 1. **a** Quiet-sun power spectra obtained by averaging power spectra of 15 time series recorded close to the centre of the solar disk. Solid curve: power spectrum of the velocity fluctuations, v (left axis), dashed curve: power spectrum of the line core intensity fluctuations, I (right axis). The horizontal lines indicate the respective 99% significance levels. **b** $v - I$ phase difference (solid) and coherence spectra. The solid horizontal bar marks the frequency range over which the cross-power exceeds its 99% confidence limit. The phase spectrum is considered reliable only in the frequency range in which the cross-power is significant and the coherence exceeds a value of approximately 0.6

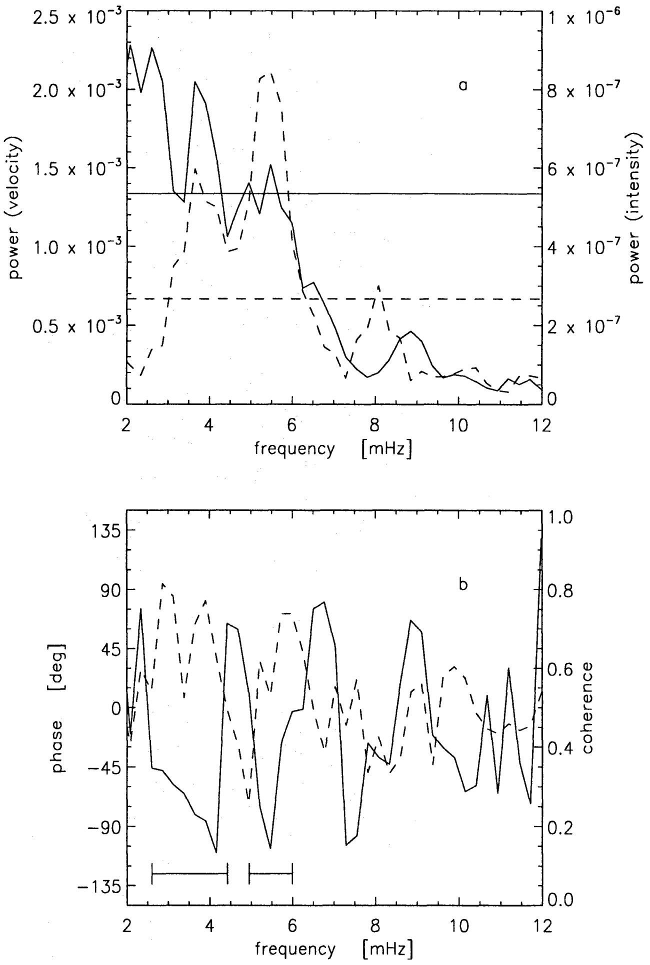

Fig. 2a and b. Quiet-sun power, phase and coherence spectra obtained near the solar limb ($\mu = \cos\theta \approx 0.07$–$0.09$, where θ is the heliocentric angle). Plotted are averages over three measurements. See the caption of Fig. 1 for details

the cores of strong CO fundamental band lines are beginning to be formed above the traditional temperature minimum layer at small μ. Nowhere on the disk, however, do we find unequivocal evidence for a truly chromospheric formation of the CO line cores (in contrast to off-limb observations). Earlier quiet-sun limb observations by Ayres & Brault (1990) were less conclusive regarding the dominant frequencies seen in these lines close to the limb, possibly due to less favourable seeing conditions (their SOL27 run, however, does show certain similarities to our data). The RMS fluctuations, taken at face value, correspond to roughly 20–25 K. However, before we can compare this value with the disk centre observations the effects of geometrical foreshortening must be compensated for near the limb where, for the same instrumental entrance aperture, the observed effective solar surface area is a factor $1/\mu$ larger than at disk centre. Thus we expect the actual fluctuations to be larger, due to the finite sizes of the oscillation cells.

To obtain a rough estimate of the true power near the limb, i.e. the power without the degraded spatial resolution, we use data kindly provided by Hofmann & Deubner (1995). They plot the RMS amplitude of the velocity and temperature fluctuations at disk centre in the 2.2 to 7 mHz frequency range at spatial resolutions ranging between $3 \times 3''$ and $19 \times 19''$. Their data are obtained from time series of core wavelength and intensity of lines formed at different heights from the mid photosphere to the upper chromosphere (Si I 1.0827 μm, Ca II 854.2 nm, Ca II K_3 and He I 1.083 μm). They also list the exponents of power law fits to the data. Over an area factor of 14 in spatial scale (corresponding to the amount of geometrical foreshortening between $\mu = 1$ and $\mu = 0.07$) the RMS amplitude of the 3 and 5 min intensity oscillations decreases by a factor of 1.9–2.6, depending on the spectral line. If we make the conservative assumption that the strongest dependence applies to the CO lines, then we need to multiply the observed intensity variations at the limb by a factor of 2.6. Converting the result into temperature we obtain $T_{\text{limb}} \approx 3790 \pm 60$ K. Here 60 K represents the RMS amplitude of the temperature fluctuations due to the p-modes.

Thus, the temperature fluctuations due to the p-modes have great difficulty cooling the gas from even the standard temperature minimum value ($\approx$ 4300–4400 K) to 3790 K. The RMS amplitude of the CO intensity oscillations, corrected for foreshortening in a simple manner, is an order of magnitude smaller than the required amount. The p-modes definitely cannot cool the gas down to 3000–3600 K, i.e. to temperatures inferred from detailed modelling of CO lines (Solanki et al. 1994). The present analysis then suggests that the p-modes are not the main source of the cool gas in the chromosphere. We have, however, not considered the effects of shadowing (cf. Ayres 1991, 1995; Ayres & Rabin 1996) or of possible highly non-linear behaviour.

Even if we assume that shadowing and non-linear effects, together with projection effects at the limb reduce the oscillation amplitudes in a way corresponding to spatial smearing by a factor of 14 each in the direction perpendicular *and* parallel to the solar limb then the measured limb temperature fluctuations must be increased by a maximum factor of 7.6, giving an upper limit on the temperature fluctuations of 190 K, which is still much too small.

The above estimates imply that the RMS of the I oscillations at the extreme limb is a factor of 1–3 times larger than at $\mu = 1$. This is under the assumption that the oscillations seen in the CO lines are not fundamentally different from those seen in other lines formed at similar heights (no obvious evidence is found to the contrary, e.g., from a row of time-series we observed with different spatial resolutions). The small temperature fluctuations we observe near the limb are not compatible with a generally hot chromosphere, which is periodically cooled to low temperatures, but are compatible with the scenario painted by Carlsson & Stein (1995) and in particular Avrett et al. (1996) of a pervasively cool chromosphere with hot shock waves passing through it. Below a height of 900–1200 km the CO molecules survive the heating during the shocks and show the time-averaged temperature, while atomic lines reveal the hot shocks.

Due to the small power in v the phase lag between v and I is less well determined at $\mu \lesssim 0.1$ than at $\mu = 1$. The cross-power is, however, significant in two intervals designated by horizontal bars in Fig. 2b and centred on the 3 min (5–6 mHz) and 5 min (2.5–4 mHz) bands, respectively. In the 5 min band the result is not too different from that at $\mu = 1$. The absolute value of $\Delta\phi$ increases from $-50°$ to roughly $-100°$ between $\nu \approx 2.5$ and 4 mHz. In the higher frequency window (5.5–6 mHz), however, the ν dependence of $\Delta\phi$ is opposite, with $\Delta\phi$ decreasing (in absolute magnitude) rapidly from roughly $-100°$ to approximately 0°. The beginnings of such a behaviour can be seen in the $\Delta\phi$ spectrum of Na I 5896 observed at $\mu = 0.8$ by Fleck & Deubner (1989).

3.3. Plage

Power, phase and coherence spectra of I and v averaged over 12 observations in active-region plages near disk centre are shown in Fig. 3. We use the CO lines themselves to make sure that the active region time series sample areas with sizable magnetic filling factor, since the CO line depths react very sensitively to magnetic filling factor due to the heating of the upper photosphere in the magnetic elements. Only time series with average line depth $\langle d \rangle < \langle d_{\text{quiet sun}} \rangle - 6\sigma$ are counted as plage, where σ is the RMS of the intensity fluctuations of the quiet sun time series ($d = (I_c - I)/I_c$ at the line core, where I_c is the continuum intensity). The average d for the 12 plage times series is 0.195, compared to 0.268 for the quiet sun at $\mu = 1$ (both values uncorrected for spectral smearing), corresponding to a spatially averaged temperature enhancement of approximately 330 K if we assume that the continua are at the same temperature.

The plage intensity shows little power above the noise (RMS fluctuations are a factor of 3–4 lower than in the quiet sun, i.e. power peaks approximately a factor of 10 lower). The power in the velocity is reduced by a factor of roughly 3 relative to the quiet sun. Only 5 min and 4 min oscillations are seen, the 3 min range shows no significant power. The reduced power and the shift to lower frequencies in active regions are consistent with observations in other spectral lines, although these refer to the magnetic network (e.g. Deubner & Fleck 1990; Lites et al. 1993; Von Uexküll & Kneer 1995). The reduced I power relative to the v power at 5 min, however, is not seen to the same extent in other lines (e.g. the Ca IR triplet lines, Deubner & Fleck 1990).

A simple 2-component model of a plage, with a hot magnetic component (composed of magnetic elements or flux tubes) filling a height-independent fraction α and a cool non-magnetic component filling the rest of the surface, should, we expect, have some difficulty in explaining these observations if the atmosphere between the flux tubes is similar to the quiet sun and α is not too large (typical of plage). Such a model should show similar oscillations as the quiet sun, simply reduced in amplitude (in accordance with observations in atomic spectral lines), since the CO lines will be formed at the usual quiet sun height between the magnetic elements and hardly at all within the magnetic elements. The different amplitude ratios of line depth to velocity oscillations in quiet sun and plage appear to contradict this model. We suggest that the expansion of the hot flux tubes with height and their merging near the traditional temperature minimum level plays an important role. The steep outwards increase in temperature found in flux tubes (e.g. Bruls & Solanki 1993; Briand & Solanki 1995) and their expansion force the thermophobic CO lines to be formed lower in the atmosphere. At greater depth, however, thermal fluctuations are more efficiently damped, so that the ratio of the velocity to intensity fluctuations is expected to increase in plage. The lower oscillation frequencies seen in plage are also suggestive of a lower formation height, although we expect that the frequency shift is partly due to a difference between the wave excitation spectrum in plages and the quiet sun.

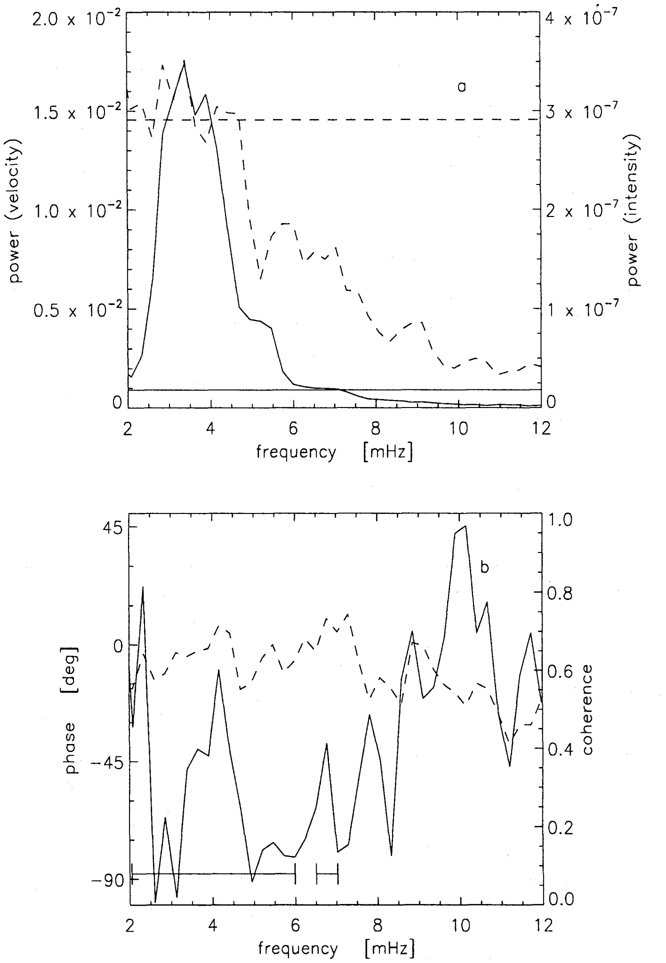

Fig. 3a and b. Averaged power, phase and coherence spectra obtained near disk centre in active region plages. For details see Fig. 1

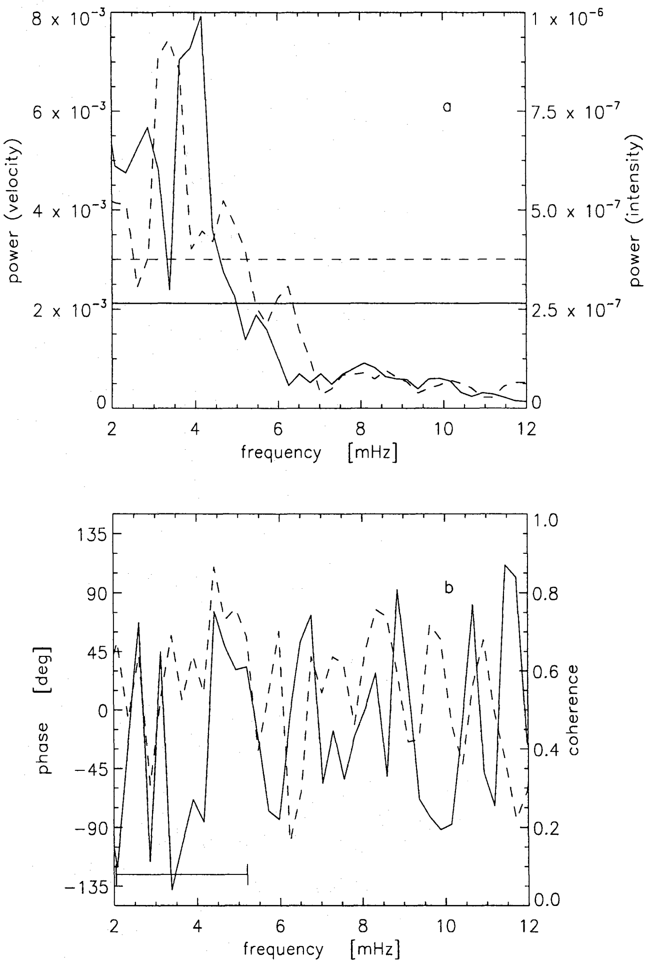

Fig. 4a and b. Same as Fig. 1 for plage near the solar limb

The picture, however, becomes more complex when considering the phase. In the ν interval in which the cross-power is more than 99% significant we find evidence for 3 regimes in $\Delta\phi$: around 3 mHz, and between 5–6 mHz, $\Delta\phi \approx -80°$, but around 4 mHz $\Delta\phi \approx -30°$ (ranging between $-10°$ and $-50°$). If correct this *could* imply the presence of propagating acoustic waves in the cool parts of active regions, i.e. mainly outside the magnetic elements. Such waves may either be fed by flux-tube wave modes leaking out into the field-free medium (e.g. Ryutov and Ryutova 1976; cf. Ryutova 1990), or may simply be excited by the changed granulation in active regions. There may also simply be excess radiative damping in this frequency interval. We caution, however, that the coherence hovers around 0.6 in most of this interval, not surprising in view of the low power of the intensity oscillations, so that considerable care must be taken when interpreting these results. Further observations would be helpful. Note that the $\Delta\phi$ spectrum seen in CO is quite different from that seen in the Ca II IR triplet lines (8542 and 8498 Å), which show $\Delta\phi \approx -70°$ to $-100°$ (Lites et al. 1982a, Deubner & Fleck 1990).

Finally, we have obtained time series in plages near the solar limb at $\mu = 0.34$ and $\mu = 0.23$. Their averaged power spectrum is shown in Fig. 4. The limb plage I power is roughly half as strong as the quiet sun power at the same μ and is not significantly lower than at $\mu = 1$, while the power in v is approximately the same in quiet sun and plage and very low in both.

The phase spectrum is reminiscent of noise and we do not discuss it further.

3.4. *Umbrae*

In sunspot umbrae close to $\mu = 1$ the wavelength shifts show more power at higher frequencies than quiet-sun spectra; the strongest peaks lie roughly at 3.5 and 6 mHz (Fig. 5a, solid curve). The line depths, however, are not much larger than in the quiet sun, $\langle d \rangle$ (4.6657 μm) = 0.285 in umbrae vs. 0.268 in the quiet sun (uncorrected for spectral smearing, etc.). The small magnitude of this difference is, we expect, due to the relatively flat temperature stratification in umbrae; the lines are much broader in umbrae, though, with prominent damping wings, so that they are much stronger than in the quiet sun, as expected. In

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a dark umbra the measured line depth corresponds to a temperature of roughly 3300 K (corrected for instrumental degradation, following the prescription given in Sect. 2.2), which is the minimum temperature of the coolest Maltby et al. (1986) umbral atmosphere, model E. Since this temperature is averaged over different parts of umbrae (we did not pick out particularly dark areas), there are probably locations that are cooler still (see e.g. Ayres 1996, who finds temperatures well below 3000 K in the upper photosphere of an umbral core.

The oscillations in I show little power in the 5 minute range and a dominant peak at 2.5–3 min (Fig. 5a, dashed curve), which again corresponds to a shift towards higher frequencies relative to the quiet sun. The umbral RMS amplitudes of the intensity fluctuations are only 60% of the disk centre quiet-sun value. Whereas the power in the 5 min oscillations is reduced by roughly a factor of 5, in good agreement with previous observations, it is enhanced somewhat in the 3 min range (see Lites 1992 for a review of umbral oscillations). The ratio of the power in I relative to that in v is approximately the same as in the quiet sun for the 4 and 5 min peaks. The CO power spectra are relatively similar to those exhibited by other spectral lines formed in a similar height range (e.g., Fe I 5434 Å, Lites & Thomas 1986), with differences not being larger than the typical variation from one umbra to another.

We find no significant dependence on the size of the umbra, with a small and warm umbra exhibiting power spectra similar to a larger cool umbra. The differences between them are not larger than between different locations in a given umbra (e.g. Uexküll et al. 1983).

The $v - I$ phase difference of umbral oscillations, as revealed by CO lines, is to be trusted between roughly 2.5 mHz and 7.5 mHz (Fig. 5b). Over this frequency range $\Delta\phi$ progresses from roughly -90° to around -130°, thus reaching considerably larger absolute phases than in the quiet sun and in plages.

The $\Delta\phi$ of CO differs significantly from the $\Delta\phi$ observed by Lites (1986) in lines formed in the umbral upper atmosphere (Ca II H and K, He I 10830Å), which exhibit $-90^\circ \lesssim \Delta\phi \lesssim 0^\circ$, whereas the CO lines show $\Delta\phi \lesssim -90^\circ$ throughout. The K line observations of Uexküll et al. (1983) in their umbra No. 2, however, reveal a close similarity to the phase behaviour of our CO observations, inspite of the probably different heights of formation. Finally, the Ca II 8542Å line in the umbra observed by Lites et al. (1982b) exhibits an even more negative $\Delta\phi$, as does Ca II K in umbra No. 1 studied by Uexküll et al. (1983). Thus the CO oscillations lie well within the large bandwidth of oscillatory properties observed in the low chromosphere of sunspots.

Of possible interest is an umbra whose power spectra show a particularly simple form, as illustrated in Fig. 6. The velocity exhibits only two relatively sharp peaks, a photospheric and a chromospheric one. Only the chromospheric peak is visible in the intensity power spectrum. Power spectra of almost the same simplicity are seen at various locations in this umbra, which appeared to have an exceptionally regular oscillatory pattern, at least in CO, which samples mainly the coldest parts of the umbra (these were sought out during observational set-up).

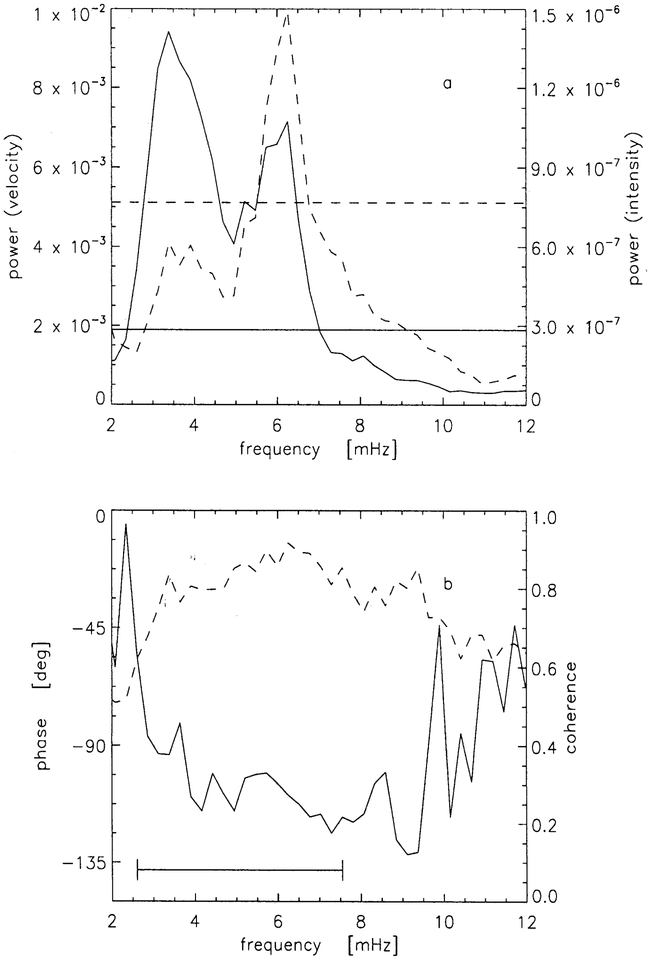

Fig. 5a and b. Same as Fig. 1, but for umbral data obtained near disk centre

4. Conclusions

We have presented and discussed power and phase spectra of CO fundamental band lines at 4.67 μm observed in different solar features (quiet sun, plage, sunspots).

At disk centre in the quiet sun our power spectra basically confirm the results of Ayres & Brault (1990) and of Uitenbroek et al. (1994). The phase difference between velocity and intensity oscillations supports the interpretation that these lines are formed near the temperature minimum at disk centre, although at low frequencies the phase behaviour of the CO oscillations deviates from that of atomic lines formed at a similar height. Close to the limb, where the CO line cores are deep and suggest the presence of very cool material at the height of the temperature minimum and the lower chromosphere (Ayres & Testerman 1981; Ayres et al. 1986; Solanki et al. 1994; Ayres & Rabin 1996), we find reduced power, particularly in the velocity. Taking into account the influence of geometrical foreshortening in a simple manner we find that the thermal oscillation is a factor of 1–3 larger than at disk centre, but still far too small to explain the low temperatures deduced from the core intensities of CO fundamental band lines at the limb in terms of cooling produced by

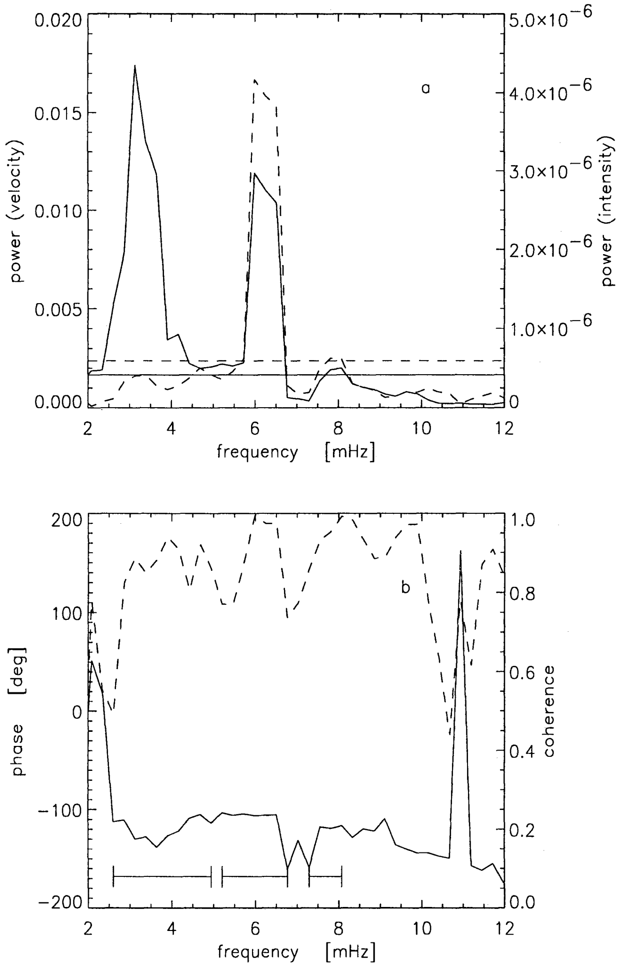

Fig. 6a and b. An example of an umbra exhibiting particularly simple power spectra. The figure is otherwise the same as Fig. 1

adiabatic expansion during an oscillation cycle. Sample calculations by Ayres & Rabin (1996) confirm that small perturbations of a standard hot chromospheric temperature cannot explain the deep CO line cores near the limb.

Our observations are more compatible with the scenario proposed by Carlsson & Stein (1995) that most of the non-magnetic part of the chromosphere is relatively cool, but is periodically heated by propagating shock waves. In their simulations atomic lines show a hot chromosphere due to the strong enhancement they obtain in the shocks. However, the time averaged atmosphere these authors obtain – which does not include cooling by the CO molecule, or the effects of granular overshoot – is still more than 1000 K hotter than temperatures derived from CO line observations (e.g. Solanki et al. 1994). Thus even this model requires considerable additional cooling to explain the low observed temperatures. Recently Avrett et al. (1996) have included CO into a model like that of Carlsson & Stein (1995). The average temperature they obtain is still too high, staying above roughly 4000 K, suggesting that in addition to CO radiative cooling mechanical cooling may also be required to obtain the low observed temperatures. Here we have presented evidence that adiabatic cooling during the expanding phase of solar p-modes is unlikely to be the main missing cooling mechanism.

The main remaining mechanism is cooling by overshooting granular material that expands near the height of the temperature minimum. This produces a dark, cold core above the white-light granule, surrounded by a bright ring where the horizontally accelerated material is braked, partly in the form of shocks (gravity waves are also present at these heights, Deubner et al. 1992). In this scenario it is these cold cores of the overshooting granules which are the seats of the CO clouds. The broad CO lines beyond the solar limb (Solanki et al. 1994), the detection of shocks in normal granules (Solanki et al. 1995) and the CO image of a dark granule with a bright ring by Uitenbroek et al. (1994) support the dynamic scenario, although observations at a higher spatial resolution are required to settle how common such negative granules are in CO. Observations by Evans & Catalano (1972), Suematsu et al. (1987) and Holweger & Kneer (1989), among others, together with striking support from numerical simulations (e.g. by Stein & Nordlund 1989) suggest that such granules are the norm rather then the exception at the classical temperature minimum layer.

The oscillations exhibited by CO in plages suggest that these lines are formed particularly deep in the atmosphere there. We speculate that CO in the upper photosphere is destroyed in the hot magnetic features that expand with height, thus forcing the CO lines to be formed deeper. Plage $v-I$ phase difference spectra (although of somewhat marginal quality) indicate $\Delta\phi$ values around -30° at 4 mHz. Additional observations are needed to confirm this small phase shift and to test whether it is due to propagating waves in the cool field-free parts of plages.

In umbrae the CO lines give results consistent with those expected from lines formed near the umbral temperature minimum and lower chromospheric level. Umbrae exhibit large phase differences between v and I oscillations (-90° to -130°). We found one umbra that showed a particularly simple oscillatory pattern, with the wavelength shift showing only 2 relatively narrow peaks, while the intensity oscillations show only a single sharp chromospheric peak.

Further studies involving radiative transfer calculations of the CO lines in the presence of cool structures with finite size (such as those discussed by Ayres 1991) and of a dynamical atmosphere are the next logical step. The extension of simulations of supersonic granular convection into the lower chromosphere are also highly desirable. There is also a need for the calculation of acoustic wave modes in the cool parts of the solar atmosphere, which are probed particularly well by CO, in order to derive the full benefit from observations such as those presented and discussed here.

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