CHROMOSPHERIC OSCILLATIONS

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ABSTRACT

This review concentrates on the quiet-Sun chromosphere. Its internetwork areas are dynamically dominated by the so-called chromospheric three-minute oscillation. They are interpretationally dominated by the so-called Ca II K2V and H2V grains. The main points of this review are that the one phenomenon explains the other (both ways), that the quiet-Sun chromosphere is a clapotisphere pervaded by shocks above \( h \approx 1 \text{ Mm} \), and that the existence of the classical temperature minimum is in doubt.

Keywords: solar oscillations, chromosphere, clapotisphere.

1. INTRODUCTION

Twenty years ago helioseismology was founded by the identification of the photospheric five-minute oscillation as the surface interference pattern of millions of solar \( p \) modes. The identification came about as synthesis between observed and computed Ulrich ridges [1] in the \( (k, \omega) \) diagram [2].

A comparable synthesis between observations and computations is now taking place for the three-minute chromospheric oscillation, a quiet-Sun internetwork phenomenon, with the temporal spectral variations of the so-called Ca II H2V and K2V as decisive diagnostic. The synthesis indicates that:

- the grains are of oscillatory nature;
- the oscillations are driven from the photosphere, with \( (k, \omega) \) ridge structure imposed by the piston;
- the internetwork chromosphere is far from hydrostatic equilibrium. Its line formation is dominated by shock interference that upsets plane-parallel height-of-formation interpretation;
- the mean internetwork chromosphere is cool but radiates in the ultraviolet as it were hot;
- infrared CO lines share in chromospheric behavior without special distinction.

Since this paper is a review, it describes much work by others; since it has a page limit, it does not do justice to much work by other others. More complete descriptions and references are given in [3], [4]. The latter review is part of the highly recommended 1994 Oslo Miniworkshop proceedings [5] of which this paper presents a summary.

2. THREE DECADES OF POWER SPECTRA

The chromospheric internetwork oscillations have been known nearly a century in their Ca II K2V grain disguise. Fourier analysis started at Mount Wilson in the sixties, just as for the five-minute oscillation. Noyes’ [6] classic diagram in Fig. 1 exhibits the characteristic power progression with height, from low-frequency intensity modulation by granulation at the bottom of the photosphere (bottom graph) through dominance of the five-minute \( p \)-modes in the photosphere (C1 and Fe I Doppelshifts) to a wide peak roughly centered at three minutes for Ca II K. The diagram demonstrates that the “chromospheric three-minute oscillation” is not exclusively chromospheric nor exclusively three-minute, facts often forgotten. Rather, the balance of dynamical power shifts with height from granulation to five-minute modes to higher-frequency fluctuations. At any height there is much overlap, which needs to be disentangled.

Figure 1: Normalized power spectra anno 1967. The bottom spectrum is for continuum intensity fluctuations. The other spectra are for Doppelshift variations of the indicated lines. They range from the deep photosphere (C1) to the middle chromosphere (Ca II K, top). The parameter \( \xi = 1.4 \nu_{\text{max}} \text{ km s}^{-1} \) from Noyes [6].

Figure 2 is from Cram’s underquoted 1978 paper [7]. It shows a similar progression in reversed panel ordering. The blob of velocity power in these quasi-diagnostic dia-


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grams again rises in frequency with increasing height of line formation. The intensity blob at right lags behind. For example, Na I D 1 resembles Ni I V, illustrating that scattering lines have deeper response for intensity than for velocity fluctuations. Higher up, H u and Ca II K share abruptly different behavior: the velocity blob is present and extends well into the propagating regime, but the intensity blob vanishes. This behavior demonstrates that something drastic happens to the intensity modulation at the formation height of these lines. In addition, low-frequency modulation appears significant in the higher-formed intensity signals. Spatially, the power occupies a fairly wide range (2–10 Mm) around wavelength \( \lambda \approx 8 \) Mm at all formation heights.

Figure 3 shows similar Cram diagrams for Ca II K features. The \( K_{1V} \) dip (left panel) resembles Ca II 8542 \( \lambda \) behavior. The \( K_{2R} \) peak (right) resembles \( K_{2V} \), but \( K_{2V} \) (middle) is closest to H u \( \lambda \). Later work has shown that the intensity ratio \( (K_{2R} - K_{2V})/(K_{2R} + K_{2V}) \) is a close proxy for \( K_3 \) Dopplershift [8]. Thus, the Ca II K core lacks line-formation symmetry; the intensity at the wavelength of the blue \( K_{2V} \) peak is primarily a velocity diagnostic.

Figure 4: Diagnostic \( \nu - k_b \) power diagrams anno 1994 for intensity fluctuations of Na I D 1 and Ca II K 2V. The solid curves again divide the three wave regimes. The dashed curves define the Lamb and fundamental modes. The structure in both diagrams has been enhanced by subtracting smooth background variations. After [9], by courtesy of Bernhard Fleck.

Finally, Fig. 4 shows the present state of the art. These Würzburg productions for Na I D 1 and Ca II K 2V fluctuations resolve Cram’s blobs into Ulrich p-mode ridges and pseudo-mode ridges higher up. The latter were earlier noted by Kneer & von Uexküll [10] and extend out to \( k_b \approx 5 \) rad\( /\)Mm and to \( \nu \approx 11 \) MHz in Na I D 1 and \( \nu \approx 9 \) MHz in K 2V. Weak interridge power is present particularly near \( \nu = 6 \) MHz [11], [12].

3. NETWORK—INTERNETWORK

Cram’s diagrams in Figs. 2–3 provide a neat summary of much of the subsequent chromospheric dynamics literature. However, they do not distinguish between network and internetwork; his slit sampled internetwork area primarily [14]. Figure 5 illustrates that such separation is necessary at chromospheric heights. The bottom panel shows photospheric p-mode power without network/internetwork difference but the middle panel
for Ca II K, V fluctuations displays marked difference between the internetwork three-minute oscillations, extending from 3 to 10 mHz, and the network fluctuations, which have much slower periodicities. The latter are not understood. They may depict stochastic granular rearrangement of network fluxtubes [15] or oscillatory phenomena such as breaking gravity waves [13], [16]. They aren’t discussed here any further, but they do need further scrutiny.

4. Ca II K, V GRAINS

K, V internetwork grains on spectroheliograms were first described and shown by Hale & Ellerman [17]. They are small (0.5–1.5 Mm), short-lived (30–100 s), come and go with 2–5 min intervals, and appear to be distributed in 2–10 Mm patterns in network cell interiors. On K, V movies they seem to be part ("the tip of the iceberg") of spider, rapidly changing structures with often large (50–100 km s⁻¹) apparent horizontal velocities. They appear very much as the whitecaps seen on the Atlantic from your plane flying to meetings as this one. They are spectrally confined to the narrow K, V peak location, but they take part in the temporal behavior of wider surroundings both spectrally and spatially [18]. A matter of debate is whether the grains mark sites of enhanced internetwork field as claimed by Sivaraman [19], [20]. More detail is given in [3], [21], [10], [4], [22], [23], [12].

The upper-left panel in Fig. 6 illustrates temporal K, V
Figure 7: Phase difference spectra between A11 3961.54 and Ca II H Dopplershifts, computed following [13]. Positive phase delay implies upward propagation in the acoustic regime. The grey-scaled dots mark amplitude-weighted phase difference per temporal frequency and per spatial position along the slit. The squares are their average per frequency bin, with rms bars. The curve in the upper half of each panel is the coherence, scaled 0–1 and determined by 9-point frequency smoothing. The lower pairs of curves are normalized power spectra, solid for A11 and dashed for Hα. Upper-left panel: slit positions 116–131" with many H2V grains (Fig. 6). Upper right: 6–15" with *persistent flasher*. Lower left: dark region at 46–57". Lower right: network at 93–106". Copied from [4]; produced by B.W. Lites from data of [8].

characteristics from NSO/Sacramento Peak spectrometry. The chromospheric network stands out as bright striping. H2V grains are seen as short-lived and small-scale brightness features in internetwork areas, especially on the right. The other panels are Fourier-filtered displays of the same data. They show that the grains are made up by combinations of long-period, five-minute and three-minute modulations. The latter have the largest weight in setting grain appearance, but display wavy-curtain patterning that is similar to the p-mode interference patterns in the five-minute panel. The temporal periodicities are of course smaller in the right-hand panel, but the morphology is qualitatively similar.

Solar oscillations are traditionally diagnosed from phase difference and coherence spectra between various diagnostics. This tactic is employed in the four Bruce Lites confosgrams in Fig. 7, with separation between various regions along the slit that are distinct in Fig. 6. The limited spatial sampling increases the scatter but the spatial separation is clearly warranted by the resulting differences. The grainy area seen at right in the upper-left panel of Fig. 6 contains increasing upward propagation over the 5–10 mHz band (upper-left panel of Fig. 7). The upper-right panel is for a small area with many grains superimposed on network-like striping. Its phase delay is close to zero throughout the region with high coherence. The lower-left panel is for a dark strip without grains and is mostly noisy. The lower-right panel is characteristic for network behavior. A slightly more extended discussion is given in [4].

The next step is to study phase relationships specifically for the brightest H2V grains. This is done in Fig. 8 by sacrificing frequency resolution for intensity characteristics. The leftward and rightward tilting of the scatter clouds in the two delay plots show that K2V intensity tends to follow three-minute A11 velocity modulation, another way of depicting the upward propagation. The grains take part in this correlation: the brightest H2V samples also tend to follow one minute after A11 redshift and two minutes after A11 blueshift. Thus, K2V grains are part of the oscillations diagnosed in Figs. 1–7.

5. NUMERICAL SIMULATIONS

The displays above establish that Ca II K2V grains are part of oscillatory phenomena in the acoustic regime. That makes them amenable to numerical simulation. The development of numerical wave modeling has gone from early scenario’s [25] – [27] and simulation [28], [29] through identification of the underlying principles [30] – [34] to detailed modeling [35] – [37] that has now reached realistic reproduction of many observed properties by Carlsson & Stein [24]. In this section I summarize some
Figure 9: Observed and computed Ca II H spectral evolution diagrams. First column: observed intensity behavior from [13]. Second column: numerical modeling by Carlsson & Stein, using a subphotospheric piston that reproduces the observed photospheric excursions for the same surface location in the data of [13]. This one-hour simulation took 50 hours CRAY supercomputer time. Third column: simulation result when the piston retains only frequencies below 4.5 mHz. Fourth column: simulation result for piston frequencies above 4.5 mHz. From [24].
of the latter results, again referring to [3] for a review of the older work.

Carlsson & Stein (abbreviated to CS henceforth)\(^1\) solve the one-dimensional hydrodynamics equations time-dependently for a stratified solar atmosphere including detailed NLTE radiative transfer. There are shortcomings, most notably the use of microturbulence (2 km s\(^{-1}\)), the neglect of line blanketing and the assumption of complete frequency redistribution, but the CS hydrogen and calcium NLTE radiative transfer modeling is of unprecedented sophistication. In addition, CS don’t employ a sinusoidal or otherwise ad-hoc imposed piston to send waves into the atmosphere. Instead, they use a many-frequency piston derived from actual observations, namely from the Doppler excursions of the Fe I line for which the observed power spectra are shown in Fig. 5. This line is present as a fast-wiggle blend in the Ca II H spectra of [13] and is formed about 100 km above \(\tau_{500} = 1\). CS transformed its observed Doppler-shift variation at a selected pixel along the slit into subphotospheric piston motion by determining a frequency-dependent transfer function that makes the piston generate the observed velocity variation at \(h = 100\) km. The question is then whether the computed behavior of the chromosphere resembles the observed behavior.

The effect of the pistonning on the higher layers is shown in Fig. 9 in the form of Ca II H spectral development diagrams, an excellent way of displaying K\(\alpha\) grain behavior pioneered in the beautiful paper of Cram & Damé [18]. The leftmost column shows the Lites et al. [13] observation. The second column shows the CS simulation for the same solar surface pixel. The computation is “sharper” since it is not affected by atmospheric seeing. After the startup period, the observation and computation are remarkably similar in their major characteristics, and even in detail. Thus, feeding the CS radiation hydrodynamics code with a photospheric piston from the Lites et al. data produces computed chromospheric Ca II H behavior much like the corresponding observed behavior. In particular, the computation reproduces the wing whistlers [38] and their apparent contraction, the sawtooth pattern of H\(\alpha\) Dopplershifts with rapid blueward and slower redward excursions, and the occurrence of bright H\(\alpha\) grains at roughly three-minute periodicity. The simulated red-shifted grains come at about the same moments as the observed ones (a 22 s phase shift is due to piston inadequacy), and there is similar alternation between sequences of bright and less bright grains. These patterns are so detailed that the good correspondence implies that the modeling is essentially correct—the more so since all earlier attempts in K\(\alpha\) grain emulation have failed, see [3]. The correspondence gets even better when CS mimic atmospheric seeing by smearing and random perturbation of their result [24].

At the start, the correspondence fails for about five minutes. The computation started from a stably stratified radiative-equilibrium atmosphere; it takes time for the piston to change that unrealistic configuration into the proper state of turmoil. In a second experiment (their Fig. 15), CS restarted the piston an hour later all over again, now using the atmosphere as it was after an hour of mistreatment. After 1000 s, a moment at which the atmosphere is relatively quiescent, both runs are nearly identical. Thus, it takes the piston 5–15 min to establish the upper atmosphere into a pattern that is fully set by the piston history and not by the previous atmosphere history. The grain patterns are set by the piston, not instantaneously but over extended time.

In another experiment, CS studied the response to the piston frequencies. The third column in Fig. 9 is the result of a simulation with piston excursions made up from only the low frequencies of the original piston. The fourth column is from the reverse case with only the high piston frequencies retained. Comparison with the original result in the second column shows that the high-frequency piston components are the more important pattern contributor, but that modulation by the low frequency components is part of grain production, just as in Fig. 6. During the first twenty minutes, the interference is destructive.

6. GRAIN FORMATION

The nice thing about Ca II K\(\alpha\) grains that originate in a computer is that their characteristics may be analyzed in detail. CS supply a sequence of informative line formation diagrams in [24] of which Fig. 10 is a specimen for \(t = 670\) s (second column in Fig. 9).

The computed intensity profile is shown in the top panel of Fig. 10 (lower curve) on a Dopplershift scale (blueshift positive). It has a prominent H\(\alpha\) grain at \(\Delta \nu = 9\) km s\(^{-1}\). The grey scaling of this panel shows the value of the intensity contribution function \(C_I(\Delta \nu, z) \equiv dI/dz\). The grain originates from \(h = 1.0\) Mm (bright blob). At that height, the velocity (jagged curve at center, shown in all panels) has a 4 km s\(^{-1}\) peak that marks an upward travelling disturbance. Higher up, such waves have steepened into shocks that run into back-falling matter from earlier shock passages; the matter just above \(h = 1.4\) Mm comes down at 10 km s\(^{-1}\).

The other three panels portray the breakdown

\[
C_I = \frac{d}{dz} \int_0^{\tau} j_\nu e^{-\tau_\nu} d\tau \\
= \kappa_\nu S_\nu e^{-\tau_\nu} \\
= [S_\nu] \left[ \tau_\nu e^{-\tau_\nu} \right] \frac{d \ln \tau_\nu}{dz}
\]

with \(j_\nu\) the volume emission coefficient, \(\kappa_\nu\) the volume extinction coefficient, and \(S_\nu\) the total source function.

The latter is shown by the dashed curve and the grey scaling in the second panel. It follows the Planck function \(B_\nu\) (dotted curve) in deep layers (bright band), but it drops away from \(B_\nu\) above \(h = 0.8\) Mm due to NLTE scattering. The latter smoothes the response of \(S_\nu\) to the large temperature contrasts across the shocks considerably. Only the lowest disturbance at \(h = 1.0\) Mm leaves a marked \(S_\nu\) increase, shown as the bright bar. It is constant across the panel because the simulation assumes complete redistribution over the line profile while the continuum contribution to \(S_\nu\) is negligible at this height.

The factor \(\tau_\nu \exp(-\tau_\nu)\) in the third panel peaks around \(\tau_\nu = 1\). The latter heights are marked by the dark curve at the center of the bright strip, also shown in the other panels. This factor selects the profile formation height. The damping wings set in at \(\Delta \nu = \pm 10\) km s\(^{-1}\). The core part is strongly affected by the shocks and changes much with time. The steep drop around \(\Delta \nu = 10\) km s\(^{-1}\) at this particular moment results from the large velocity change at \(h = 1.4\) Mm. Above this height, the redshifted line-center extinction produces opacity up to \(\tau_\nu = 1\) out to \(\Delta \nu \approx -10\) km s\(^{-1}\). No further opacity is added in the first 500 km below this height because there this part of the profile sits well outside the Doppler core. Thus, this part of the profile is “formed” over the extended range \(h = 0.6\) to \(1.6\) Mm without any height discrimination. In contrast, the \(\tau_\nu \exp(-\tau_\nu)\) weighting function peaks sharply at the grain-formation height in the left-hand side of the panel.

The bottom panel of Fig. 10 shows the opacity scaling factor \(d(\ln \tau_\nu)/dz = \kappa_\nu/\tau_\nu\). This factor is large at frequencies and heights with much extinction at small optical
small (dark holes in the panel) in areas where the Doppler core has shifted to other frequencies while the overlying matter is opaque. This factor is the main producer of line-profile asymmetry. At $h = 1.0$ Mm the local extinction $k_e$ peaks at $\Delta \nu = 4$ km s$^{-1}$ Dopplershift (velocity curve), but the steep gradient $d \nu_c / dh$ at this height skews this weighting factor into a brightness blob centered at 8 km s$^{-1}$. Its apparent blueshift is increased by the presence of slower-moving material just above it. This blob, multiplied with the factors in the other two panels, produces the $K_{30}$ grain at apparent $\Delta \nu = 9$ km s$^{-1}$ in the emergent intensity profile. It wins from the other blobs in the upper-left panel by the $S_e$ multiplication, and it is narrowed in $\Delta \nu$ by the $\tau_e \exp(-\tau_e)$ formation height factor.

Figure 10 shows that $K_{30}$ grains form from the combination of upward traveling disturbances with a local temperature increase and downfalling matter at larger height. This combination has indeed often been proposed as grain-formation scenario [3]; CS have proven it in detail.

![Figure 10: Ca II H line formation diagram for $t = 670 s$. Top: intensity contribution function $C_I$ (brightness coded), emergent profile (lower curve), vertical velocity $v_e$ (jagged curve in the middle), and $\tau_e = 1$ height. The latter two curves are also shown in the other panels, which represent a breakdown of $C_I$ into the three brightness-coded factors indicated at the upper left in each panel. From [24].](image)

![Figure 11: Temperature modeling of the solar chromosphere. FALA (dot-dashed) [30] is the newest update of the standard empirical modeling by Avrett and coworkers. The dotted curve gives the radiative-equilibrium stratification of the initial atmosphere in the CS simulation. The two thin solid curves mark the range, at each height, of the temperature variations reached during the simulation. Above $h = 1.0$ Mm the temperature varies over all the diagram but the higher values are only reached temporarily within short-duration shocks. The thick solid curve is the temporal mean. It is close to the initial stratification, implying that the shocks have not heated the mean atmosphere. The thick dashed curve is the result of modeling computed time-averaged ultraviolet continuum brightness temperatures with a best-fit hydrostatic temperature stratification. It displays an apparent chromospheric temperature rise. From [24].](image)

### 7. CHROMOSPHERIC NATURE

Figure 11 displays another CS experiment [24], [41]. It compares the range of actual simulation temperatures per height with the temporal mean. It also shows the input radiative-equilibrium atmosphere, a standard semi-empirical Harvard model, and a semi-empirical model derived in Harvard fashion from the mean ultraviolet brightness temperatures delivered by the simulation. The latter has a chromospheric temperature rise much like the standard model, but the actual mean temperature does not. The latter shows that shock dissipation does not produce significant heating over the input radiative-equilibrium atmosphere during the one-hour run; the outward increase of the former is due to the nonlinear response of the Planck function to temperature increase. The high-temperature spikes in the shock fronts con-
Clapotisphere

"The extensive literature on the K$_{1}$ grains and related cell-interior phenomena leads us to the conclusion that bright cell grains are of hydrodynamical origin, due to oscillations that are present all over the solar surface but which produce grains only at places and moments set by pattern interference between the velocity oscillations in the K$_{1}$ layer and the evanescent wave trains of the p-mode oscillation deeper down. They remind us of what is called "clapotis" on sea charts for areas where wave interference produces waterspouts on the ocean (Dowd 1981)."

Rutten & Uitenbroek 1991

"When the crests of such waves coincide, their amplitudes combine, creating huge standing waves, much steepler than traveling waves. This phenomenon is called "clapotis". Off the northern tip of New Zealand, where major wave patterns collide in deep water, clapotis is regularly seen. The pin-nacing waves formed here have so much vertical power that they can throw a laden kayak clear out of the water."

Dowd 1981

Contribute overly much emission, and so skew the observed mean brightness temperature to higher values than the actual mean temperature.

The nonlinear brightness sensitivity to the temperature spikes implies that modeling the quiet-Sun atmosphere by multiple components that exist side-by-side, each in hydrostatic equilibrium as if it were an extended plane-parallel atmosphere, is no longer a viable approach above $h = 1$ Mm. Not only must the network and an internetwork regimes be modeled with height-dependent geometry and pressure balances between them [42], but also the internetwork departures from hydrostatic equilibrium are sufficiently large that the dynamical variations are not to be averaged away as linear variations around a mean value. The internetwork chromosphere is inherently a clapotisphere (Fig. 12).

8. DISCUSSION

8.1 Phases. Skartlien et al. [43] determined phase relationships in various combinations from the computed $I$ and $V$ behavior of the Ca II lines in the CS simulation. There are parallels and discrepancies with observations [4], [44]. I don’t think the discrepancies disprove the general validity of the clapotipheric picture that emerges from the simulation. Phase differences are very sensitive to the exact details of line formation and therefore to the quantitative details of the complex patterns in Fig 10. In particular, the relationships of the Ca II infrared red lines to H & K are intricate and depend strongly on the adopted microturbulence and frequency redistribution [45].

Observationally, this sensitivity is evident from the large differences between the three internetwork panels of Fig. 7. Another, yet unpublished example is that Lites and I have found that those spatio-temporal internetwork sites that display the most outstanding sequences of H$_{1}$ grains characteristically show deviating $V$ - $V$ phase difference behavior for various diagnostics, tending to zero rather than propagative delays in the three-minute band. A likely explanation is that these mark downdraft sites.

In addition, phase determinations may be jeopardized by atmospheric seeing [8]. Unpublished experiments by Skartlien on the CS simulation results indicate that seeing may cause phase copying from low to high frequencies [8] which needs to be taken into account when comparing high-frequency phases between different diagnostics [46].

Figure 12: \textit{Clapo-ti-sphere} n. [O.l. Fr. \textit{clapotis} from ON klåppa + Cl. G sphere], shell around star or planet with sufficient wave interaction to upset hydrostatic modelers and boaters. Ex.: 1. Ca II K is clapotisphere. 2. internetwork clap (vulg.).


8.2 CO lines. Turning the low chromosphere into a clapotisphere also explains Ayres’ cool CO clouds [50], [51]. The mean temperature in Fig. 11 decreases in radiative-equilibrium manner out to $h = 1$ Mm, just as in Avrett’s newest empirical model [52] from the line-
Figure 14: Filtered CO time-slices. Left: brightness temperature of the 3-2 R14 transition in the fundamental rotation-vibration CO band near 4.67 μm. Right: Dopplershift of the same line. Upper panels: low-frequency components showing convective overshoot. Lower panels: 3-5 min oscillatory components. From [49].

center brightness temperatures of ATMOS-observed CO lines across the infrared. The absence of the classical chromospheric temperature rise above h = 500 km adds sufficient CO opacity at sufficient low temperature to explain the observed CO limb darkening [53]. Of course, the temperature spikes in the shocks carry less weight in the infrared.

The amount of CO peaks in the upper photosphere as shown in Fig. 13 from Leifsen [47]. In a clapotisphere without mean temperature rise, CO has a longer tail of presence towards larger height but even then the CO response functions peak in the photosphere. They are wider than for atomic lines because they are set on the deep side by the dissociation of CO, not by exp(−τv) cutoff. They are also more sensitive to temperature variations. For CO, higher temperature causes dissociation and reduces the opacity so that deeper, yet hotter layers are observed. For infrared continua and many atomic lines, the opacity and source function temperature sensitivities work against each other because temperature increase causes population increase.

The time slices in Fig. 14 from [49] prove the photospheric character of CO-line formation on the disk. The observed behavior is very similar to the behavior seen in the wings of the Ca II H & K lines. The granulation panels show convective overshoot, while the oscillation panels show upper-photosphere oscillation patterns. There are no long-lived dark clouds.

Figure 15: Scatter diagrams as in Fig. 8 for the grain-rich 116–131μm segment in Fig. 6, correlating H2V intensity against the low-frequency component of the continuum intensity (granulation). The time delays between the continuum sampling and the H2V sampling are from top to bottom: 0 min, 1 min, 2 min, 5 min and 10 min. Panels 3 and 4 indicate that the brightest H2V grains follow 2–7 min after a dark phase of the granulation. Data of [8].

8.3 Pistons. The observations in Fig. 6 and the split-frequency simulations in Fig. 9 show that K3V grains are a multi-frequency phenomenon. In the CS simulations, the (k, ω) ridge structure at photospheric levels is incorporated realistically although the simulation is only one-dimensional, because the pistonning is derived from
the observed Fe I Dopplershifts. The latter are dominated by the global p-mode oscillations and contain the p-mode interferences as present at the simulated location and time. The CS simulation is only one-dimensional, but the actual piston that they used is not: It possesses full knowledge of ambient and passing disturbances at photospheric height.

The CS piston-repeat experiment indicates that the piston behavior dictates the clapotipspheric K$_{2V}$ behavior, with time delays of 5-15 min needed to govern the higher atmosphere reproducibly. Thus, the (k, $\omega$) ridge structure that is observed for K$_{2V}$ intensity in Fig. 4 probably derives from the (k, $\omega$) obedience of the underlying piston. In particular, the latter may impose the high-frequency pseudo-modes in Kumar fashion [54] as well as (k, $\omega$) phase structure [23]. However, not all of the K$_{2V}$ characteristics seem to be set globally. As mentioned above, the brightest grain trains possess markedly deviating phase behavior. In addition, Fig. 15 indicates that the brightest H$_{2V}$ grains tend to follow 2-7 minutes after the underlying photosphere contained a dark intergranular lane. The body of these scatter clouds does not show correlation with the low-frequency brightness at any time lag, but the few points with the largest H$_{2V}$ intensity favor the lefthand side in the third and fourth panels significantly. It is interesting to note that similar correlation plots of H$_{2V}$ internetwork intensity against photospheric five-minute amplitudes at similar delays show only a smaller effect; p-mode excursions do not seem to have the role in grain excitation that has often been attributed to them. Visual inspection of the co-spatial K$_{2V}$ and G-band movies of Brandt et al. [55], [56] also indicates a correlation between the spatio-temporal patterning of H$_{2V}$ internetwork extremes and intergranular lane morphology, rather than a correlation with photospheric p-mode pattern extremes.

This apparent intergranule connection seems to fit earlier observations of Muller and recent results of the NJIT group [57], [58] who find that high-velocity events in the photosphere, presumably contributing significantly to p-mode excitation, occur preferentially above dark sites in the granulation. Perhaps these events excite exceedingly bright K$_{2V}$ grains as well. If that is the case, such local spatial dependences do not conform to global (k, $\omega$) ridge structuring. They therefore seem a likely explanation for the interridge power at 6 MHz seen in Fig. 4. Its concentration to $\nu = 6$ MHz may then be interpreted as atmospheric cutoff-frequency wake response [43] to high-amplitude disturbances (at low clapotipspheric temperature) rather than be attributed to the chromospheric mode invoked by [11], [12].

### 8.4 Internetwork fields.

Sivaraman’s claim [19], [20] that K$_{2V}$ grains and their brightness are set by internetwork fields is disputed but not disproven. This apparent correlation has been attributed to persistent flashers [3], [55], which are loose patches of field (perhaps previously part of the network) that migrate through network interiors as if they were Lockheed corks. In fact, Brandt et al. [56] found that their K$_{2V}$ flasher indeed follows the cork trajectory defined by the horizontal flows derived from granulation tracking.

Higher up, the clapotipspheric role of canopies remains unclear. The Mg II h and k lines are similar to Ca II H & K with larger opacity. Recent data [60] indicate that K$_{2V}$ and K$_{2}$ peaks occur everywhere, a result that seems to require a classic chromospheric temperature rise just above the Ca II H & K formation heights. However, the complexities of Fig. 10 show that detailed modeling is also needed for these lines. In particular, Mg II h & k photons suffer yet more from resonance scattering since they lack the escape route that the Ca II infrared lines offer to H & K photons. Increased spatial smoothing may result, both radially and horizontally.

He I 1083 nm doesn’t offer a clearcut diagnostic either. Its Dopplershifts tend to follow H & K Dopplershifts faithfully but at smaller amplitude [8]. One may conclude that He I 1083 nm is formed below H & K or that the oscillation amplitude decreases with height, but it seems more likely that the complex formation of this line again necessitates detailed modeling rather than simple height-of-formation response estimation. The long vertical bar of brightness in the third panel of Fig. 10 upsets such interpretation already for the more simple case of Ca III; the sensitivity of He I 1083 nm opacity to coronal radiation makes this line a much more confused diagnostic [39]. The point is proven by Fig. 16 which displays large-scale pattern variations. I wonder whether the large-scale coherency at left and in the middle portray H-o-like fibril oscillations.

### 8.5 Internetwork jets.

Another intriguing correlation is shown in Fig. 17. It is based on HRTS VI data and part of a manuscript-in-preparation by Hoekzema (not Hoeksema), Rutten & Cook. It shows that internetwork locations with excess C 1156 nm Dopplershift, called “chromospheric jets” in earlier analyses by Dere et al. [62], [63], tend to participate in a 160 nm brightness oscillation [64] - [66] with three-minute periodicity and antiphase between red jets (top curve) and blue jets (bottom curve). There is no direct one-to-one correspondence per pixel; these relations only emerge after averaging over large area. Hoekzema [61] speculates that the confusion arises from interference between upward propagating shock trains, shock-incident chromospheric undulations and f-mode waves that run transversely along canopies. The latter then produce the observed small wavelengths (1.2–1.4 Mm); the interference produces much variation; large blueshifts and redshifts result from constructive combination.

Data of much longer duration and larger spatial extent than HRTS rocket flights furnish are needed to substantiate such ideas. However, the point is that C1 internetwork Dopplershifts seem related to the three-minute oscillation described above. The apparent velocities are large, but may be overestimated by the HRTS data re-
duction procedures since they interpret displaced emission components in optically thin fashion whereas the CI lines are very thick. The H$_{2}$V grain in Fig.10 sits blueshifted at twice the actual velocity at its formation height, which is the maximum upward velocity in the whole atmosphere at that moment. Similar formation of emission peaks in the ultraviolet CI lines, with substantial skewing from $dr/dv$ gradients caused by steep velocity gradients along the line of sight, may well enhance the apparent Doppler shifts over the actual ones. Obviously, here is work for SUMER and for CI line formation simulation.

8.6 Internetwork spicules. A first speculation concerns spicules. Conventional wisdom says that limb spicules correspond to the network mottles or fibrils seen in Hα on the disk. However, in a thoughtful review Garaasokas [67] argues that spicules are neither mottles nor fibrils. I wonder whether they have to do with internetwork clapotis?

9. CONCLUSION
The proceedings of the 1994 Oslo Miniworkshop [5] may be compared to the proceedings of the 1975 Nice Colloquium [68]. Both books have their cover adorned with a diagram equating observed and computed oscillation characteristics. In the Nice case, it was Deubner's $(k, \omega)$ diagram showing the first glimpse of the Ulrich ridges [1]. In the Oslo case, it is a Carlson-Stein diagram with the first two columns of Fig. 9, showing that K$_{2V}$ grains are also due to acoustic waves.

The first diagram started helioseismology. Is the second diagram of any future use? Ascribing grains to clapotispheric interference doesn't seem to make them worthwhile diagnostics. Perhaps the brightest ones are. The correlation noted in Fig. 15 suggests that these may mark high-speed downdraft sites of strong $p$-mode excitation.

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