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Solar Atmospheric Dynamics

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Abstract. This review focuses on acoustic oscillations in the solar atmosphere. There is much debate on photospheric pistons to chromospheric oscillations, on the penetration height of acoustic shocks, and on their contribution to chromospheric heating, with new input coming from space observations and from numerical simulations. Less progress is made in identifying wave modes or wave heating in magnetic structures, but it seems that umbral flashes are ripe for understanding.

1. Introduction

The title above is a tautology. There is no such thing as a static solar atmosphere even though we teach students to assume it plane-parallel (e.g., Rutten 1999b[1]). The abstract for a contribution by A.M. Title and the TRACE team to this meeting states: *"The primary conclusion is that the outer atmosphere of the Sun is finely structured and dynamic"*. That concerns the million-degree solar corona as seen by TRACE[2], but the same may obviously be concluded for the solar photosphere and chromosphere.

In addition, the title is overly general. "Atmosphere" implies everything solar between interior and heliosphere. "Atmospheric dynamics" suggests a review of all things solar excepting neutrino's, seismology, dynamo mechanisms, abundances and the solar wind — but even helioseismology delivers *p*-mode asymmetries which may stem from photospheric dynamics, and even the FIP-sensitive ion abundance anomalies of the solar wind may be caused dynamically in chromospheric domains where hydrogen is still neutral.

I therefore restrict this review to acoustic oscillations in the chromosphere, and aim it at non-solar cool-star colleagues. For solar-oriented reviews of this topic see Rutten (1995, 199a), Carlsson & Stein (1998), Judge & Peter (1998), Ayres (1998), Rutten et al. (1999), Deubner & Steffens (1999), and see Ulmschneider (1999) for cool-star overtones.

A brief introduction to chromospheric oscillations is furnished by three figures of textbook stature. Figure 1 is Noyes' 30-year old display demonstrating the existence of the "chromospheric three-minute oscillation", in addition to the

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[1] http://www.astro.uu.nl/˜rutten

[2] http://chippewa.nascom.nasa.gov/TRACE

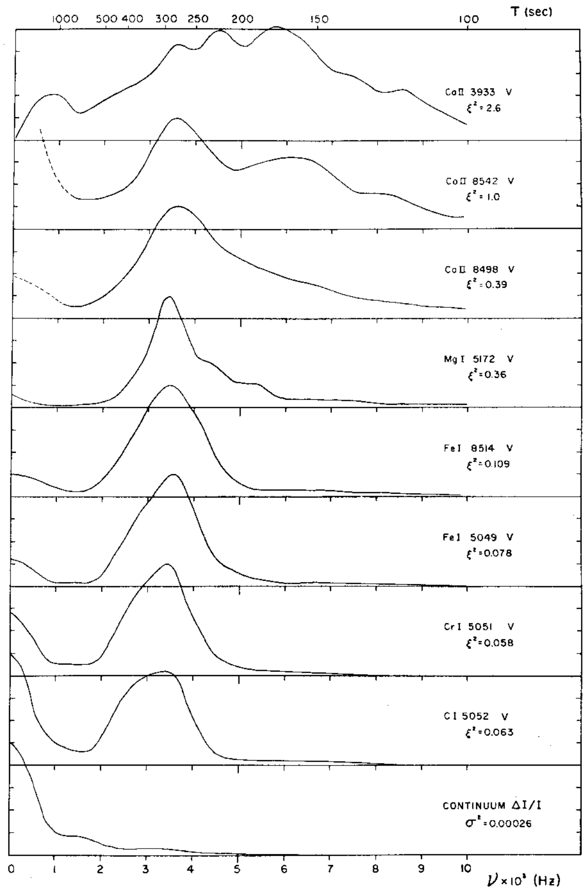

Figure 1. Dopplershift power spectra for a sequence of spectral lines with increasing height of formation from bottom to top. The lowest graph is for continuum intensity. The variance $\xi = \sqrt{2}\, v_{\rm rms}$ km s^{-1} corresponds to equivalent microturbulent broadening. From Noyes (1967).

photospheric five-minute oscillation. The name has often been misinterpreted as meaning exclusively chromospheric and/or exclusively at 180 s periodicity, but the figure shows that the Dopplershift power peak widens gradually with height, from a relatively narrow peak around 5 min ($\nu = 3.3$ mHz) in the very deep photosphere sampled by the C I line (7.7 eV excitation energy) and the Cr I line (equivalent width only 20 mÅ), to a much wider peak spanning $\nu = 2 - 9$ mHz for the Ca II K line center. There is no clear five/three-minute dichotomy with height, rather a shift in dominance.

Figure 2 displays quasi-(k, ω) spectra from Cram (1978), ordered reversely with highly-formed Ca II K in the bottom panels. The spatial decomposition assumed azimuthal symmetry through use of the Abel transform on one-dimensional data taken with a stationary spectrograph slit. More modern renderings from two-dimensional Dopplershift data resolve the familiar p-mode power ridges. Nevertheless, the contours in Cram's diagrams illustrate key properties. The

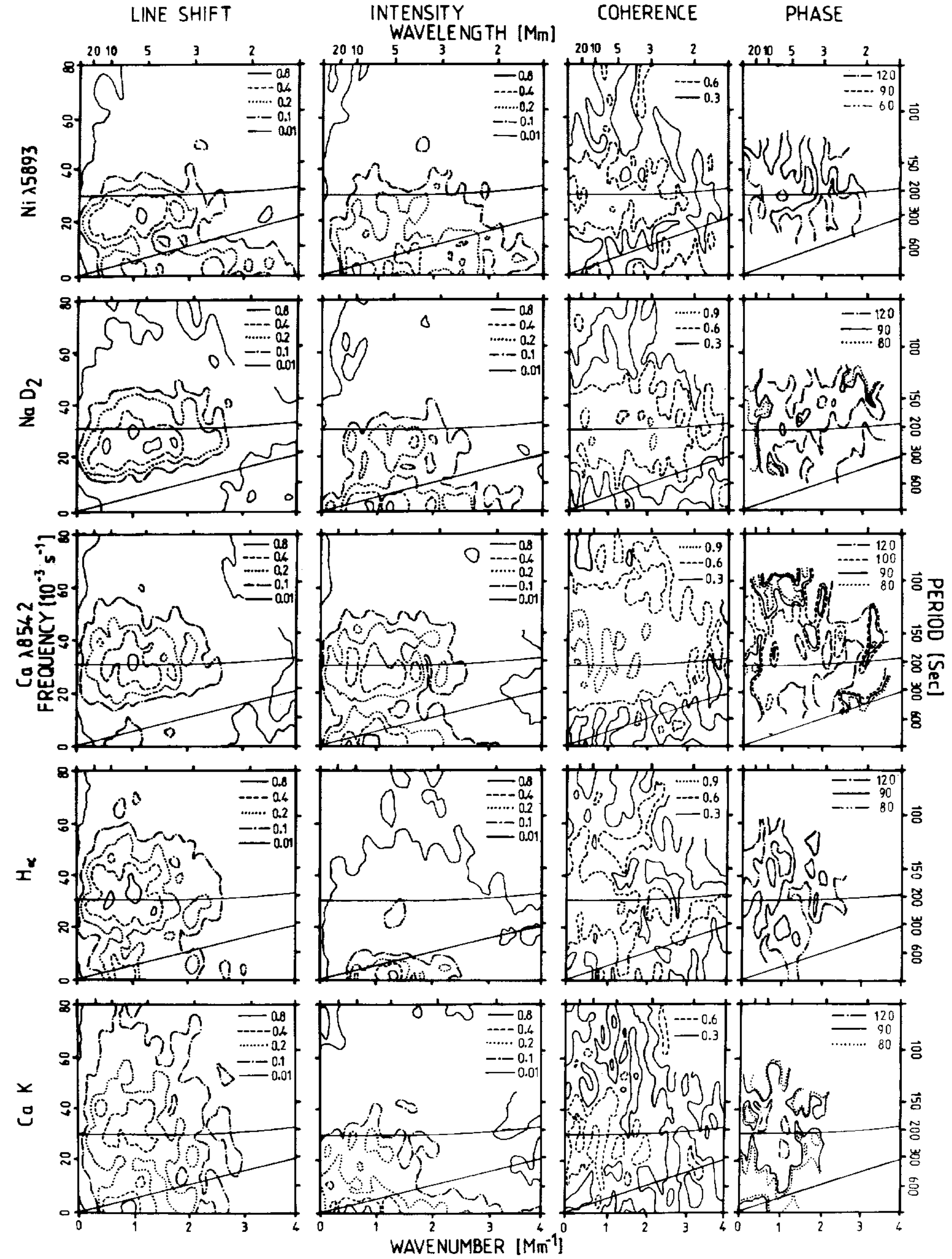

Figure 2. Dopplershift (V), intensity (I), V–I ccoherence and V–I phase difference Fourier (k, ω) diagrams for lines formed at different heights. Axes: temporal frequency $\omega = 2\pi/P$ (period P added at right) against horizontal spatial wavenumber $k_h = 2\pi/\Lambda_h$ (wavelength Λ_h added on top). The solid curves separate the acoustic propagation domain (top part), the evanescent domain (wedge in the middle), and the gravity wave domain (bottom part). From Cram (1978).

Dopplershift power peak migrates upwards and extends to high temporal frequency for increasing line formation height, but does not grow significantly to higher spatial frequency (lefthand column). The intensity power blobs in the second column behave initially as the Dopplershift power but do so at a lag: the Na I D_2 intensity power distribution resembles the Ni I 5893 Dopplershift power more than it does Na I D_2 intensity power. Higher up, Hα and Ca II K seem to drop out in intensity. The coherence and phase difference spectra display complex patterns in which it is not easy to separate signal from noise.

Cram's Fourier spectra were an early but comprehensive demonstration of the information content available in power, phase difference and coherency spectra from Dopplershift and intensity diagnostics formed at different heights. Numerous papers since have refined such analysis; a nearly complete list is quickly obtained from ADS[3] by searching for oscillation papers authored by Deubner, Fleck, Kneer, Lites, or by inspecting their ADS-distilled publication lists and abstracts on my own website[4]. The Fourier resolution increased, resolving p-mode ridges, "pseudo" ridges above the cutoff frequency, and the interridge (k, ω) domains. The measurement sensitivity increased, permitting studies of the (k, ω) background. Spatial sampling improved, permitting separation of the network and internetwork contributions to quiet-sun oscillations. Nevertheless, many puzzles remain; the final (k, ω) analysis isn't yet in (Deubner & Steffens 1999).

Part of the problem of Fourier-analyzing solar atmospheric oscillations is that taking Dopplershift and intensity as proxies for vertical motion and temperature at "the height of line formation", as represented by the $\tau = 1$ Eddington-Barbier characteristic photon escape depth, is too much a simplification for chromospheric lines with complex NLTE formation. For example, the Na I D lines are chromospheric in the sense that their cores have $\tau = 1$ in the chromosphere, but their intensity does not respond to the presence of a chromospheric temperature rise even in the static case (Bruls et al. 1992; Stuik et al. 1997), making them effectively photospheric.

The Ca II H & K line centers are chromospheric even in their intensity response (meaning that their source function is not yet fully uncoupled from the thermal structure at the height where the chromospheric temperature rise sets in in standard plane-parallel models of the solar atmosphere such as VALIIIC of Vernazza et al. 1981), but their intensity response to atmospheric oscillations is sufficiently complex that it takes very detailed modeling to describe how these lines respond to atmospheric oscillations. Numerous such attempts were made through the years in order to understand the Ca II K quiet-sun oscillatory behavior characterized by the so-called internetwork grains (Athay 1970; Cram 1972; Liu & Skumanich 1974; Mein et al. 1987; Leibacher et al. 1982; Rutten & Uitenbroek 1991; Rammacher & Ulmschneider 1992; Fleck & Schmitz 1991b, 1993; Kalkofen et al. 1994; Sutmann & Ulmschneider 1995a, 1995b). Although some of these efforts were rather sophisticated, they failed to explain the observed behavior. That was finally achieved through the yet more sophisticated time-dependent NLTE radiation-hydrodynamics simulation of Carlsson & Stein

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[3] http://adsabs.harvard.edu/abstract_service.html

[4] http://www.astro.uu.nl/~rutten/rrtex/bibfiles/ads

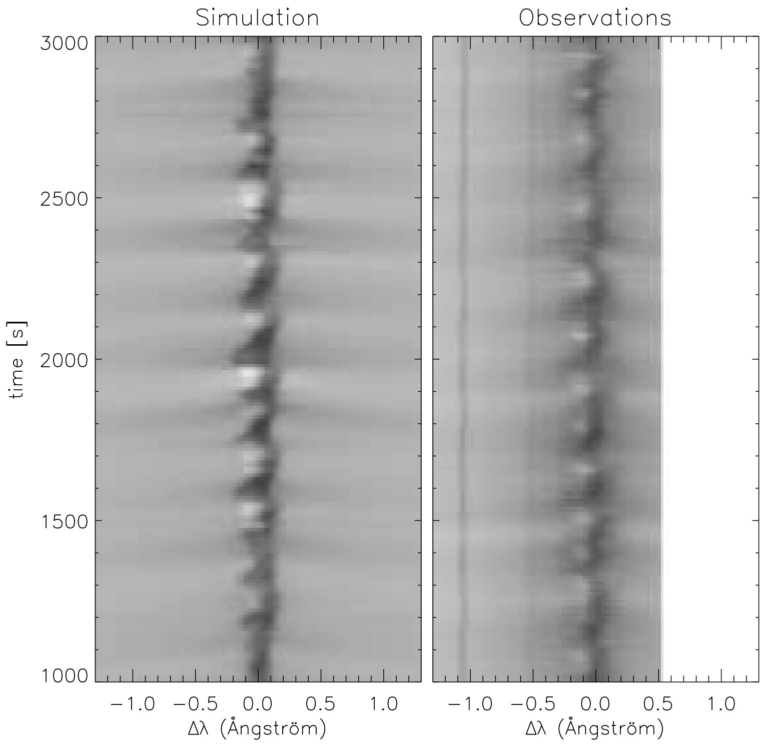

Figure 3. Comparison between observed (right) and computed (left) spectral evolution of the Ca II H core for a quiet-sun internetwork location. The simulation matches the repetitive line-center shifts, dark "whisker" contractions and bright H_{2V} "grain" occurrences quite well. Cover illustration of proceedings edited by Carlsson (1994).

(1994, 1997) who convincingly explained the solar phenomenon as due to vertically propagating acoustic waves of various frequencies that steepen and coalesce into weak shocks at about the height of Ca II K core formation. Some of the earlier efforts were on the right track and came close; Carlsson & Stein settled the issue by reproducing the Ca II H time-sequence observations of Lites et al. (1993) in detail, deriving the piston input to their simulation from the observed Dopplershifts of a photospheric Fe I line and presenting the Ca II H output from the simulation in spectral evolution plots that are directly comparable to the actually observed behavior in the format which best displays the intrinsic detail (Cram & Damé 1983). The initial comparison is reproduced in Fig. 3.

The Carlsson–Stein grain reproduction was a breakthrough success story at previous Cool Star Workshops (Carlsson & Stein 1992, 1996) and figures heavily below in subsequent discussions whether specific pistons exist, whether the shocks contribute heating, and to what height they penetrate into the chromosphere. To conclude this introduction, it serves here to illustrate the intrinsic complexity of chromospheric dynamics. Even though the physics of the internetwork grain phenomenon is chiefly one-dimensional and non-magnetic (at least in the simulation!), large effort and expensive allotments of supercomputer time were required to identify its cause. There is no hope that this might have been accomplished by direct inversion akin to the techniques that are employed so fruitfully in helioseismology, and that are being developed with increasing success for photospheric modeling here at the IAC (e.g., Ruiz Cobo et al. 1992, 1997; Bellot Rubio et al. 1997, 1998; Westendorp Plaza et al. 1998; Socas Navarro et al. 1998). Inversion of Ca II K oscillation data was in fact tried by Mein et al. (1987) in much the same manner as the inversion schemes now being set up by the Meudon group to interpret Hα spectrometry from THEMIS (Molowny-Horas et al. 1999). Such multi-parameter inversions are a step up from cloud-model interpretation and may fare fairly well for stable optically thin structures, but the Ca II K grain story indicates that "forward modeling" using full-physics "self-consistent" simulation is required for any dynamical phenomenon harboring chromospheric radiative transfer. It is an enormous challenge, however, to tackle the inherently multi-dimensional and magnetism-dominated dynamical Hα chromosphere this way. Judge & Peter (1998) judged the chromosphere "possibly the most difficult region of the Sun"; chromospheric researchers will stumble along the first steps of the methodology path *scenario formulation* ⇒ *forward simulation* ⇒ *data inversion* for some time to come.

2. Acoustic pistons in the deep photosphere

The Carlsson-Stein internetwork grain simulation is one-dimensional but because its piston was derived from observed photospheric Dopplershifts, the simulation took the multi-dimensional environment containing granulation flows, p-mode interferences, gravity waves, magnetic tensions and whatever else contributes to photospheric Dopplershifts, properly into account. It is a broadband piston; subband experiments described in Carlsson & Stein (1997) show that its broadband character is essential to obtain satisfactory reproduction of the observed Ca II H core behavior. That result does not specify whether there are specific locations that may be identified as solar pistons causing enhanced chromospheric three-minute oscillations and internetwork grains.

A lingering debate is whether internetwork concentrations of magnetic field act as such pistons. The many pro-and-contra references are given in Lites et al. (1999), who find no evidence for such correspondence at the (relatively high) sensitivity of the HAO-NSO/Sacramento Peak Advanced Stokes Polarimeter, with recent corroboration from Worden et al. (1999) who compared TRACE images with NSO/Kitt Peak magnetograms. The issue hinges on the nature of internetwork magnetism. A long sequence of reports, started by Livingston & Harvey (1971) and most recently added to by Lin & Rimmele (1999), has claimed the existence of small-scale internetwork field concentrations of which the size and the intrinsic strength diminished over the years and which in my opinion hasn't settled on anything conclusive yet. I think it likely that magnetic field concentrations well above the Hanle-effect background exist in intergranular lanes, temporarily swept together by granular flows, but that these don't reach the collapsed-fluxtube strengths required to impede granular convection and its production of acoustics as noticeably as in the abnormal granulation caused by dense kilogauss fluxtube concentrations in active network and plage.

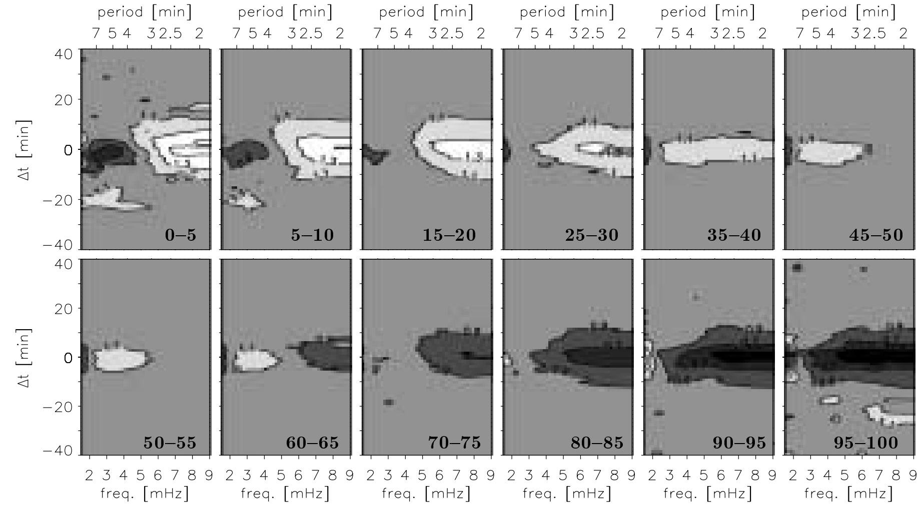

Figure 4. Time-delay charts of the co-location probability between photospheric brightness modulation as function of frequency (periodicity along the top) and granular brightness, both properties measured over 15-min duration, and with averaging over many space-time samples. Grey: space-time average. The time delay (vertical) is positive for brightness measured after modulation amplitude. The bright peak in the first chart indicates that 2–3 min modulation favors the darkest 5% of the granulation brightness distribution, with a symmetrical deficit for the brightest 5% (last panel). From Hoekzema et al. (1998).

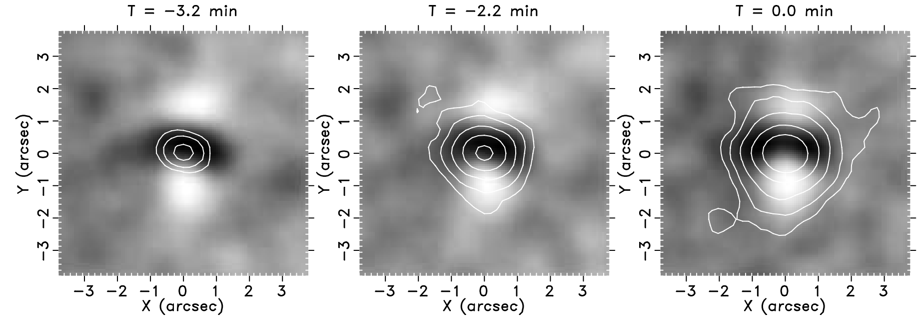

Figure 5. Acoustic flux contours superimposed over underlying granular morphology, averaged over seismic events diagnosed as upward propagation followed by downward propagation in phase differences between Fabry-Perot Dopplershift measurements at different photospheric heights. The granular scene was rotated per event to have the intergranular lane horizontal; 2000 event scenes where then averaged per delay bin with delay $T = 0$ min at the event peak. The survival of the lane in this averaging shows that seismic events co-locate preferentially with preceding intergranular lanes. From Goode et al. (1998).

The quest for granular pistoning meets more success. Figure 4 displays spatio-temporal "correspondence" maps from Hoekzema et al. (1998) which show that, statistically, the darkest intergranular lanes go together with a slight surplus of 2–3 min power in photospheric brightness. Kiefer & Balthasar (1998) refined this by identifying f-mode oscillations as having the largest co-location probability with dark lanes, while Hoekzema & Brandt (2000) find a similar small but significant co-location preference between high-amplitude sites and mesoscale convergence in the granulation pattern. Figure 5 from Goode et al. (1998) displays similar co-location preference between granular morphology and an acoustic flux measure based on Dopplershift phase difference sampling in two-dimensional Fabry-Perot spectrometry (cf. Restaino et al. 1993). Figure 5 averages the acoustic flux and the local granular scene over many occurrences of a "seismic event" marked by an up-and-down propagation sequence in Dopplershift. It shows that such event selection leads to statistically significant spatial co-location with a dark intergranular lane during the preceding minutes. Goode et al. (1998) claim that these seismic events constitute the source of the solar p-modes. That needs confirmation, but enhanced wave excitation by small darkening features agrees well with the acoustic-source scenario developed by Rast (1999) and the acoustic shock generation from a small vanishing granule occurring in the detailed 3D radiation-hydrodynamics simulation in Skartlien's important but still unpublished 1998 PhD thesis[5].

3. High-frequency acoustics in the high photosphere

Carlsson & Stein (1995) added a controversial experiment to their internetwork grain simulation through a Skartlien-made graph showing that the weak grain-causing shocks produce an apparent chromospheric temperature rise when the resulting time-averaged ultraviolet continua are fitted in static VALIII-like fashion, even while the time-averaged temperature remains as low as in static radiative-equilibrium (RE) stratification, because the nonlinear Planck function sensitivity to temperature in this wavelength region favors the high temperatures in the shock fronts. The conclusion that the solar atmosphere remains basically cool out to $h \approx 1000$ km, much higher than the VALIIIC temperature minimum at $h \approx 500$ km, has been attacked by Ulmschneider (1999) and colleagues (Theurer et al. 1997; Kalkofen et al. 1999) who argue convincingly that Carlsson & Stein's piston lacked high frequency power because it was derived from observed Dopplershifts with too wide a line response function. Taking that for granted, Cuntz et al. (1999) succeeded in modeling overall cool-star Ca II K line-core behavior (the "Ca II flux" including its "basal flux" component) with two-component acoustic and magnetic heating.

On the other hand, the static RE stratification is yet higher than the radiation temperatures of infrared CO lines which should obey LTE and portray real temperature. This dichotomy has long and forcefully been admonished by Ayres (e.g., Ayres & Testerman 1981; Ayres 1981; Ayres et al. 1986; Ayres & Wiedemann 1989; Ayres & Brault 1990; Ayres & Rabin 1996) but will not be

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[5] http://www.astro.uio.no/~roarsk/phd.html

explained without time-dependent CO formation computation in a dynamical simulation (cf. Uitenbroek et al. 1994; unpublished review by Avrett[6]). My own suspicion remains that an internetwork area may sometimes lack in acoustic pistoning and so get the chance to develop catastrophic CO cooling along the lines of Kneer (1983), Muchmore & Ulmschneider (1985) and Muchmore et al. (1988) to temperatures well below static RE at heights as high as $h = 1000$ km, while at other times increased heating from multiple "seismic events" makes the same area hot — relating the dynamical upper-photosphere stratification to the deep-photosphere piston distribution issue of the previous section, even if not yet worrying about the canopy variation issue of the next section.

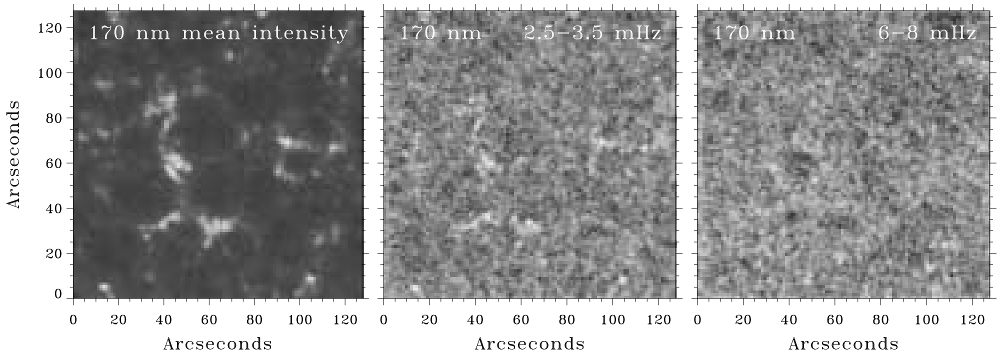

Figure 6. Fourier power maps from a 90-min TRACE 170-nm image sequence taken May 12, 1998, of a quiet area near disk center. First panel: time-averaged brightness, showing patches of fairly strong network. Middle panel: relative power per pixel for 5-min modulation. Third panel: relative power per pixel for 2-min modulation. From Krijger et al. (in preparation).

What about observing the supposedly present high-frequency oscillations? Figures 6 and 7 result from Fourier analysis of TRACE near-ultraviolet image sequences of the upper photosphere. TRACE imaging supplies only brightness modulation, no Dopplershifts, but TRACE does do so without noise from atmospheric seeing, with sufficient angular resolution to assess spatial power patterning, and with sufficient field extent to furnish much better statistics than obtained in slit spectrometry. The power maps in Fig. 6 illustrate once again that low-frequency modulation dominates in network areas, up to 5-min periodicity, but that network shows comparatively low power at higher frequencies except in enhanced "halos" around network patches (cf. Brown et al. 1992; Hindman & Brown 1998). The dappled power appearance in the internetwork domain in both maps seems set by noise. We should remember that in (k, ω) representation most power lies on the p-mode ridges and their pseudo-ridge extensions to higher frequencies and that the multitude of modes making up the ridges constitute a complex instantaneous amplitude interference pattern that indeed looks like noise. Thus, the co-location correlations shown in Figs. 4 and 5 hold

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[6] http://cfa-www.harvard.edu/˜avrett/genereview/gene_review.html

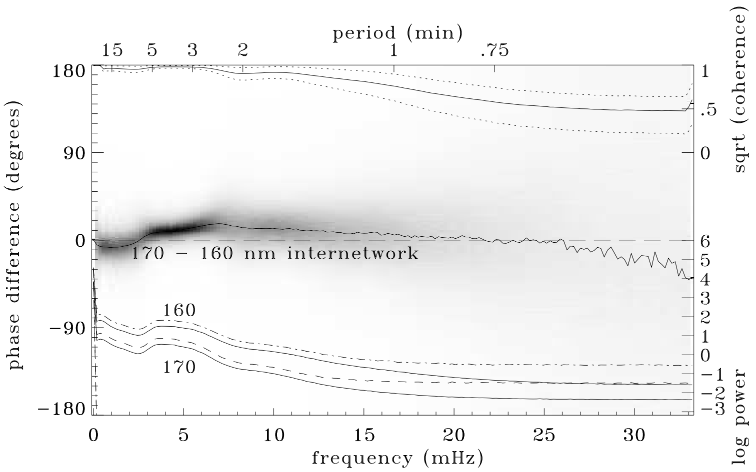

Figure 7. Fourier spectra from TRACE 170 nm and 160 nm image sequences taken May 12, 1998. The scatter plot shows the *I*–*I* phase difference between 170 nm and 160 nm brightness, in degrees (lefthand scale) per frequency bin per pixel, with the curve showing the spatial average. The curve in the upper half (scale at right) shows the coherency between the two brightnesses, obtained by frequency smoothing and spatial averaging over all pixels, with 1σ variations. The curves in the lower half are the power spectra, with 1σ variations (the lower ones fall out of the frame due to the logarithmic power scale, specified at right). Only internetwork locations were admitted to the analysis. From Krijger et al. (in preparation).

only for a small selective subset of the modulations contributing power to these maps, are far from immediately obvious, and are lost when power is mapped over long duration as done here.

Figure 7 displays corresponding TRACE Fourier spectra in a compact format developed by B.W. Lites (and known as “Lites confusogram”). The scatterplot phase difference spectrum shows signatures of gravity waves at low frequency and of upward propagating acoustic waves to about $f = 15$ mHz, but no significant power above this frequency (where the phase difference spectrum becomes unreliable because TRACE switches passbands sequentially). So even with excellent statistics and without seeing, no high-frequency signature is found. Obviously, this result should be confronted by numerical simulation of the oscillatory response of the near-ultraviolet continua as sampled by TRACE.

4. Acoustic penetration in the chromosphere

Higher up in the solar atmosphere, the penetration of acoustic oscillations into the chromosphere have been measured with the SUMER spectrometer on SOHO with conflicting results as to how high the internetwork three-minute oscillation propagates upwards (Steffens et al. 1997; Carlsson et al. 1997; Judge et al. 1997; Curdt & Heinzel 1998; Gouttebroze et al. 1999; Doyle et al. 1999; Wikstøl et al. 2000). Most authors rediscover that network oscillates only slowly (Liu & Sheeley 1971) and that intensity modulation drops out as in Fig. 2. Some authors claim that there is no propagation into the upper chromosphere, whereas others claim propagation out to the transition region. Part of this confusion stems from the instrument. SUMER is a slit spectrometer sampling a minute fraction of the solar surface, supplying poor statistics. In many observations the slit didn't track solar rotation (even when it was supposed to), and in many data sets the signal-to-noise is insufficient to determine Dopplershifts reliably.

I suspect that a large part of the confusion is intrinsically solar. V–V and I–I phase difference analysis using a stationary slit assumes a one-dimensional atmosphere, cause and effect radially connected, but at some height the three-dimensional magnetic topology upsets this assumption. High-resolution Hα movies show enormous variety in the "mottles" and "fibrils" that delineate smaller-scale and lower-lying loop-like field structures than the coronal loops imaged so beautifully by TRACE through its 171 Å passband. Areas that belong to the internetwork on magnetograms or Ca II K filtergrams can be covered thickly by Hα mottles, while others can be nearly devoid of mottles so that Hα shows the same oscillatory grains that are seen in Ca II K (and were studied in Hα by Kneer & Von Uexküll 1983, 1985, 1986). Undoubtedly, some SUMER data sets had their line of sight jutting through complex low-lying mottle canopies, while others may have had a more unobstructed view into the acoustic "clapotispheric" domain that itself reached higher by being unobstructed.

5. Magneto-acoustics in sunspot umbrae

A final note (the page limit hits here, once again I managed to say more than my allotment permits to write up): there is no progress in identifying fluxtube oscillations, but it seems that the nonlinear three-minute oscillations in sunspot umbrae seen as "flashes" in Ca II K spectral sequences are ripe for detailed understanding. An elaborate inversion was presented a few days before this meeting by Socas Navarro (1999) in his PhD thesis. Inversion may be a step too far when forward modeling through numerical simulation in Carlsson-Stein fashion hasn't been done yet, but in any case, it seems that the umbral flash phenomenon provides an extreme and therefore amenable case of acoustic shock dynamics (cf. Lites 1994).

Acknowledgments. I thank the organizers for an excellent meeting, and acknowledge a travel grant from the Leids Kerkhoven Bosscha Fonds.

Discussion

J. Linsky: Is there any evidence for the direct conversion of magnetic energy into heat or dynamics in the solar chromosphere?

R. Rutten: To my knowledge, not really. The magnetic network oscillation studies so far show only long-period power without clearly defined modes. There are lots of speculations, but I think that the issue why and how network fluxtubes get so bright in Ca II H & K or in ultraviolet lines is just as open as when you wrote your thesis on H & K thirty years ago.

P. Maltby: Let me mention that in six sunspots observed with SUMER we found clear three-minute oscillations of the whole umbra reaching into the transition region. What do you think of that?

R. Rutten: Yes, I should have mentioned your work (Brynildsen et al. 1999a,b) confirming the earlier suggestion by Gurman et al. (1982) of upward propagating umbral waves. My feeling is that this fits Lites' (1994) point that umbrae are perhaps the closest thing to a 1D radially stratified atmosphere on the Sun. In a straight-up monolithic field, the shocks should run up to larger height than elsewhere.

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