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Dynamics of the Quiet Solar Chromosphere

Robert J. Rutten

Sterrekundig Instituut, Utrecht, The Netherlands

Bruce W. Lites

High Altitude Observatory, NCAR, Boulder, USA

Thomas E. Berger, Richard A. Shine

Lockheed-Martin Solar and Astrophysics Lab, Palo Alto, USA

Abstract. The solar chromosphere has never been static although it was often modeled so. Even the quiet-sun internetwork chromosphere has become thoroughly dynamic with the acoustic shock interpretation of the Ca II K_{2V} grains. We concentrate on the latter in this brief review. Recent analysis of ASP data confirms that their excitation is more likely set acoustically than magnetically. TRACE imagery permits seeing-free studies of their occurrence patterns.

1. Introduction: network and internetwork

Figure 1 is a paradigmal cartoon taken from Judge & Peter (1998). It depicts a vertical slice through the quiet solar photosphere and low chromosphere across a single supergranular cell. Clusters of strong-field magnetic elements ("fluxtubes") sit at the cell borders and constitute the "magnetic network" seen on photospheric magnetograms. Due to the relative increase of magnetic pressure over gas pressure, their magnetic fields expand higher up and become space-filling in the chromosphere, combining into a "magnetic canopy" overlying the cell interior. Chromospheric heating (dark shading) occurs presumably preferentially along the cluster axes since the latter show up as bright 1–3 arcsec grainy patches on images taken in Ca II H & K, Ly α, and other ultraviolet lines up to considerable ionization temperature. These grainy patches constitute the "chromospheric network". It coincides with the magnetic network and outlines the supergranulation cell boundaries, but very incompletely.

The remaining quiet-sun area besides the network grains is called the internetwork. It intermittently contains bright features of its own, in particular the so-called Ca II K_{2V} grains. They have gotten this name because their intensity peaks dramatically just blueward of the Ca II H & K line centers, but they are also present, at lower contrast and a slight phase shift, on wider-band Ca II K filtergrams such as the ones in Fig. 4 and on wide-band near-UV images from

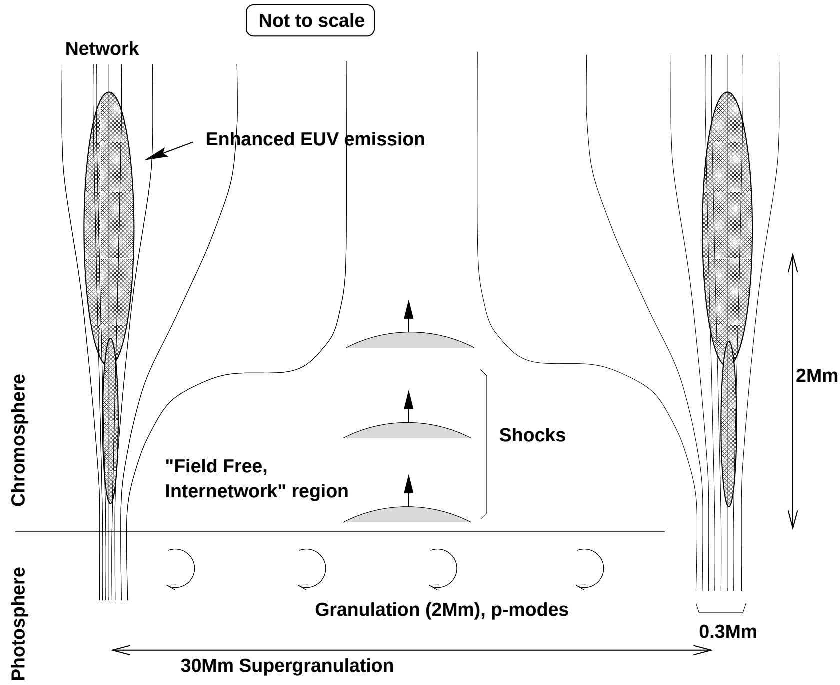

Figure 1. Schematic vertical section through a supergranulation cell with magnetic network at its borders. From Judge & Peter (1998).

TRACE such as the ones in Fig. 5 (cf. Rutten et al. 1999). We therefore call them "internetwork grains" below.

2. Fourier and grain signatures

Numerous studies (*e.g.,* Jensen & Orrall 1963, Liu & Sheeley 1971, Lites et al. 1993) have shown that the chromospheric network is characterized Fourier-wise by power at five minutes and longer periodicities, whereas the internetwork modulation tends to peak between five and two minutes. This fact is currently being rediscovered by SUMER spectroscopists. It is illustrated particularly well by spatial Fourier charts derived from TRACE image sequences (Fig. 2). The network stands out bright in single images and in low-frequency modulation maps, but the contrast with the internetwork modulation amplitudes reverses at higher frequencies.

It is likely that the slow network modulation reflects footpoint buffeting of the magnetic elements by granular dynamics (*e.g.,* Kneer & von Uexküll 1986, Wellstein et al. 1998) rather than an intrinsically oscillatory phenomenon, although long-period waves may play a role at the level of the chromosphere (Lites et al. 1993). In the photosphere, the buffeting is vividly demonstrated by the bright point dynamics in the high-resolution G-band image sequence of Berger & Title (1996) and indeed produces characteristic splitting and merging times per magnetic element of five to seven minutes (Berger et al. 1998).

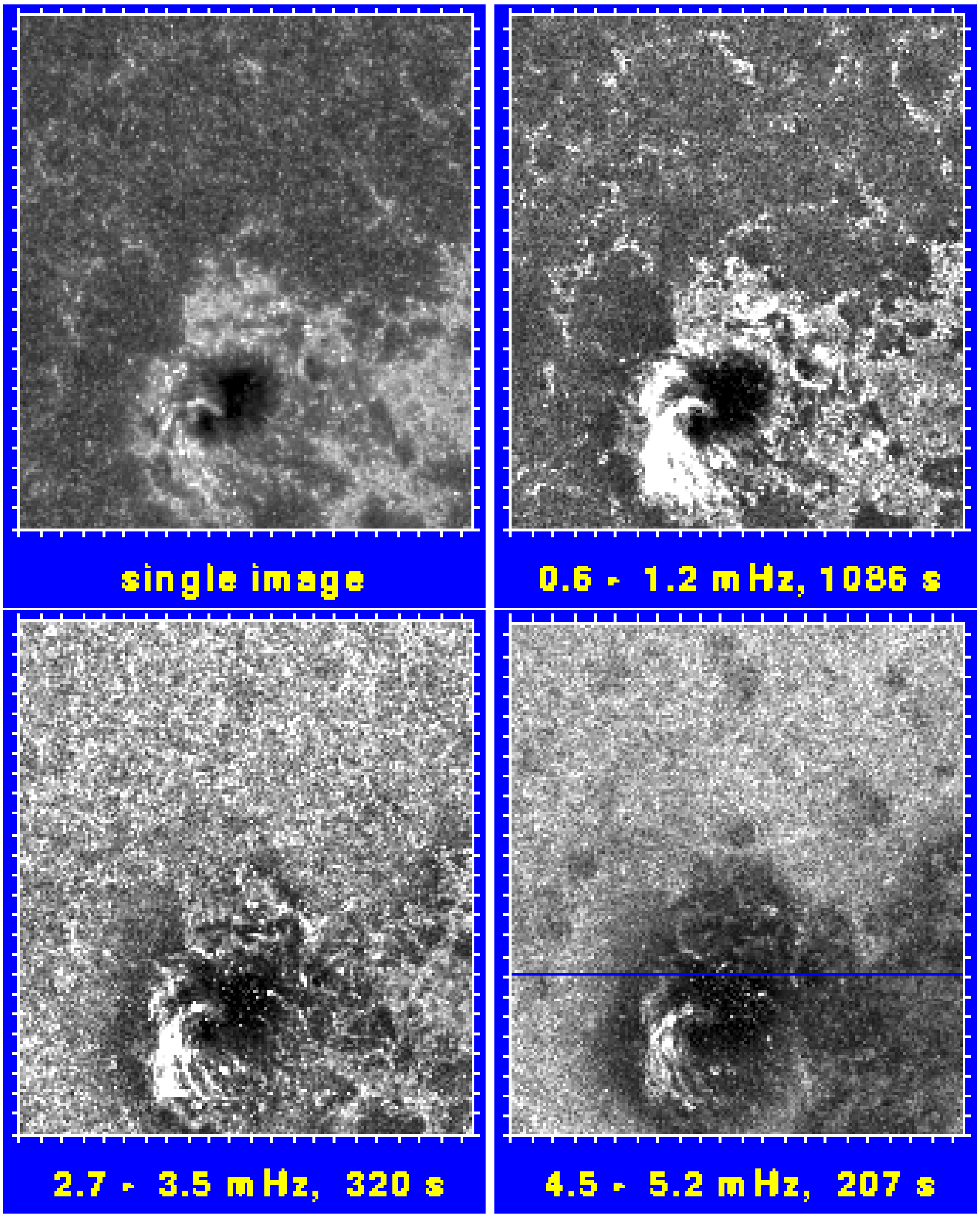

Figure 2. Fourier modulation maps constructed from a TRACE 1600 Å image sequence of AR8210 obtained during UT 08:30–11:58 on May 1, 1998. The tick marks are 10 arcsec apart. The first panel contains a sample image. The other panels display relative intensity power per pixel in the indicated frequency bin. A surge occurred during the sequence, producing relatively high power at all frequencies. Penumbral waves cause enhanced power in the second panel. Plage and network have larger power than present in the internetwork at low frequency, but the power contrast flips at higher frequencies where the internetwork modulation gains dominance.

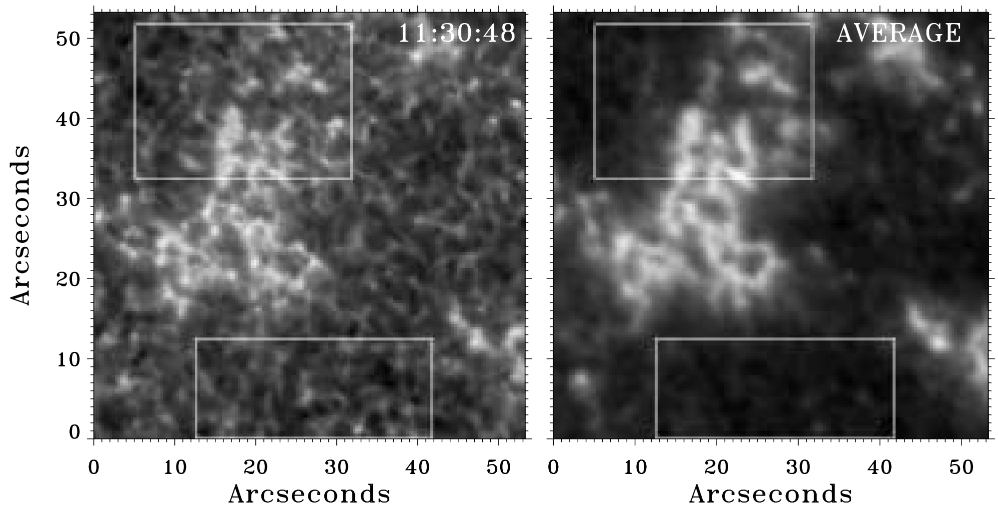

Figure 3. Left: high-resolution Ca II K filtergram taken with the Swedish Vacuum Solar Telescope at La Palma (Loefdahl et al. 1998). Right: 70-min temporal average of the same area, demonstrating the rapid variation of the internetwork brightness pattern (lower box) by showing considerable suppression of its time-averaged contrast relative to the network. From Lites et al. (1999).

For the internetwork modulation, commonly called the "chromospheric three-minute" oscillation, the intrinsic oscillatory nature is much more outspoken. The best demonstration is obtained by downloading a TRACE near-UV image sequence (for example the data taken May 12, 1998 UT 14:31–16:00, of which a small part is shown in Fig. 5) and to watch the rapid internetwork morphology changes with time. If such a movie is played fast, the network grains appear as islands of stability in a sea of motion made up of rapidly evolving, spidery patterns that often display apparent supersonic motion and that are very suggestive of wave interference.

Figures 3–5 illustrate the fast internetwork morphology changes and the appearance of internetwork grains as localized pattern enhancements that flash on and off a few times at 2–4 min intervals, frequently in pairs (Fig. 4). In addition to these ubiquitous enhancements, "persistent flashers" may occasionally migrate through an internetwork area. They probably represent the chromospheric signature of a newly-emerged strong-field ephemeral region on its way to become part of the network (Brandt *et al.* 1992, 1994).

3. Internetwork grain formation and excitation

The acoustic shock simulations of Carlsson & Stein (1997) have crowned a long sequence of efforts to model chromospheric oscillations, in particular the spectral formation of K_{2V} grains (Athay 1970, Cram 1972, Liu & Skumanich 1974, Mein et al. 1987, Leibacher et al. 1982; Rammacher & Ulmschneider 1992; Fleck & Schmitz 1991b, 1993; Kalkofen et al. 1994; Sutmann & Ulmschneider 1995a,

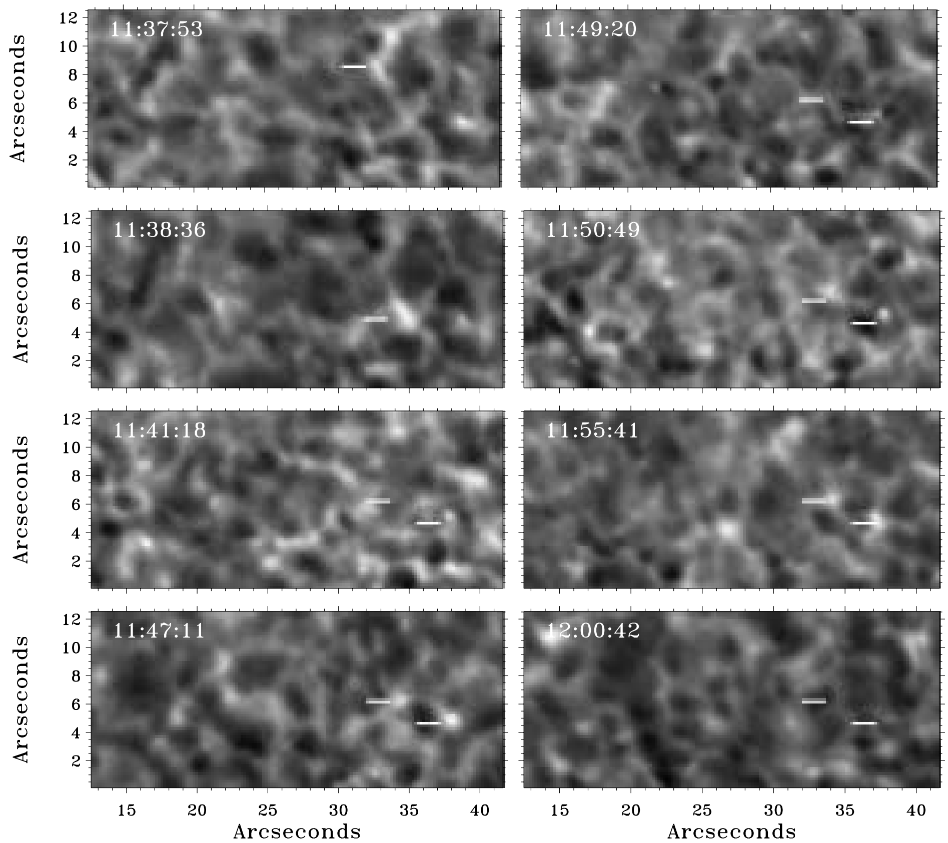

Figure 4. Selected frames from the La Palma Ca II K filtergram sequence of Loefdahl et al. (1998). The area corresponds to the internetwork region outlined by the lower box in Fig. 3. The markers in the first two frames point at a brightening which travels along a pattern ridge with apparent supersonic motion (70 km/s). The two markers in the other panels (at fixed locations) identify two concurrent recurrent K_{2V} grains which brightened, in phase, a few times at 2–3 min intervals. From Lites et al. (1999).

1995b). The extensive literature on K_{2V} grains has been reviewed by Rutten & Uitenbroek (1991) and Rutten (1994, 1995, 1996). Carlsson and Stein's detailed reproduction of observed spectrally-resolved H_{2V} grain development has ascertained beyond doubt that the grains are caused by weak acoustic shocks which propagate upwards through the low chromosphere. The marked H & K profile asymmetry (absence of concurrent H_{2R} peaks) results from substantial line-center opacity shifts caused by higher-located matter that falls back after having been kicked up by earlier shock passages.

Questions yet open are whether internetwork grains appear preferentially at specific places betraying some piston mechanism, to what extent the shocks may be diagnosed in higher layers, and whether the shocks play some significant role, for example in chromospheric heating or in the FIP element segregation

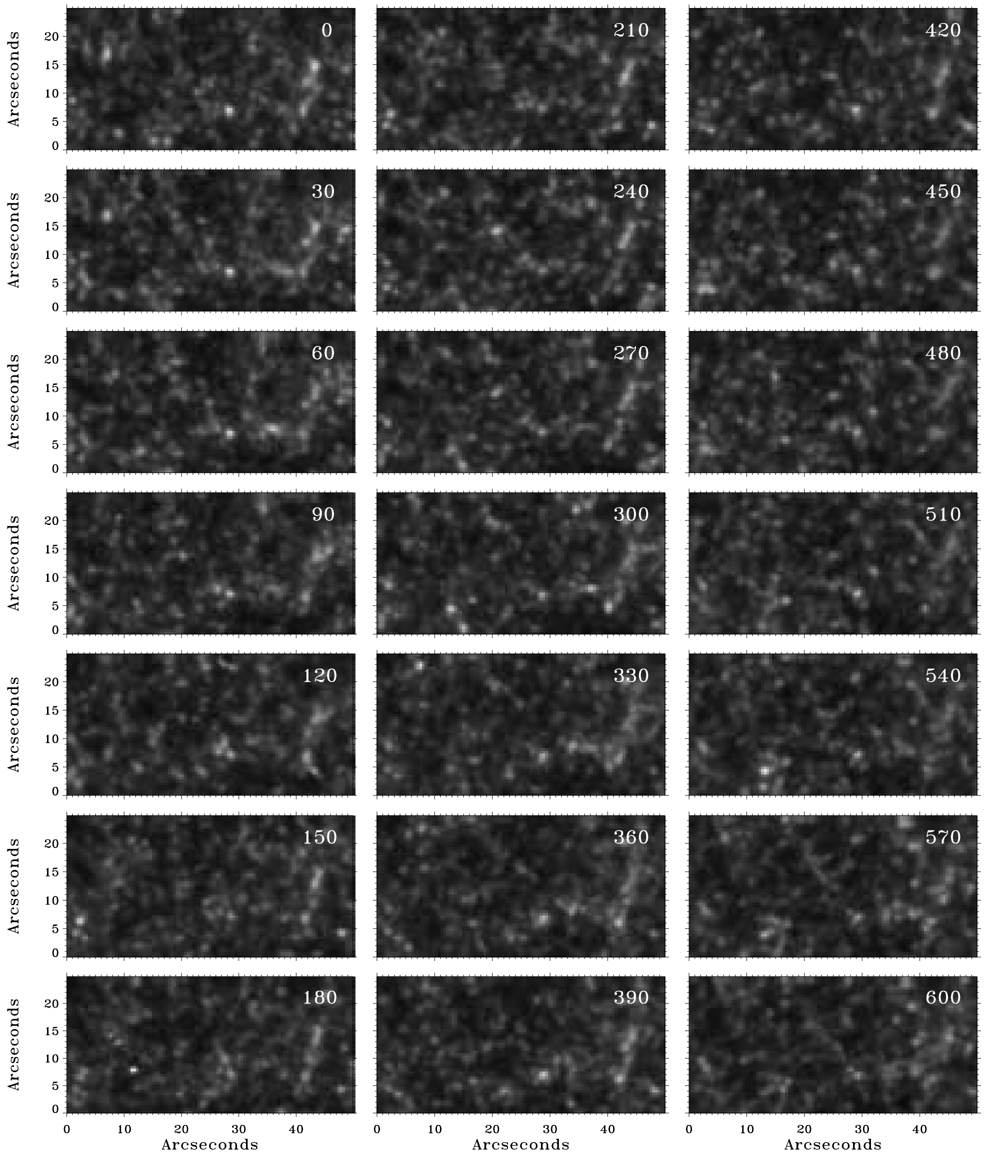

Figure 5. Cutouts from a TRACE 1550 Å image sequence (May 12, 1998 UT 15:00:26–15:10:28) illustrating quiet-sun internetwork behavior. The passband contains C IV lines that brighten at magnetic activity and C I lines that provide internetwork grain signatures. The numbers specify elapsed time in seconds.

observed in the fast solar wind. The issue of acoustic internetwork heating is addressed by Ulmschneider and by Cuntz elsewhere in these proceedings. For the FIP flip issue see Rutten (1998) and other reviews in Fröhlich et al. (1998).

The question to what height the shocks penetrate recognizably is a matter of debate in the current literature, mostly on the basis of SUMER spectrometry (*e.g.,* Steffens et al. 1997, Judge et al. 1997, Carlsson et al. 1997, Curdt & Heinzel

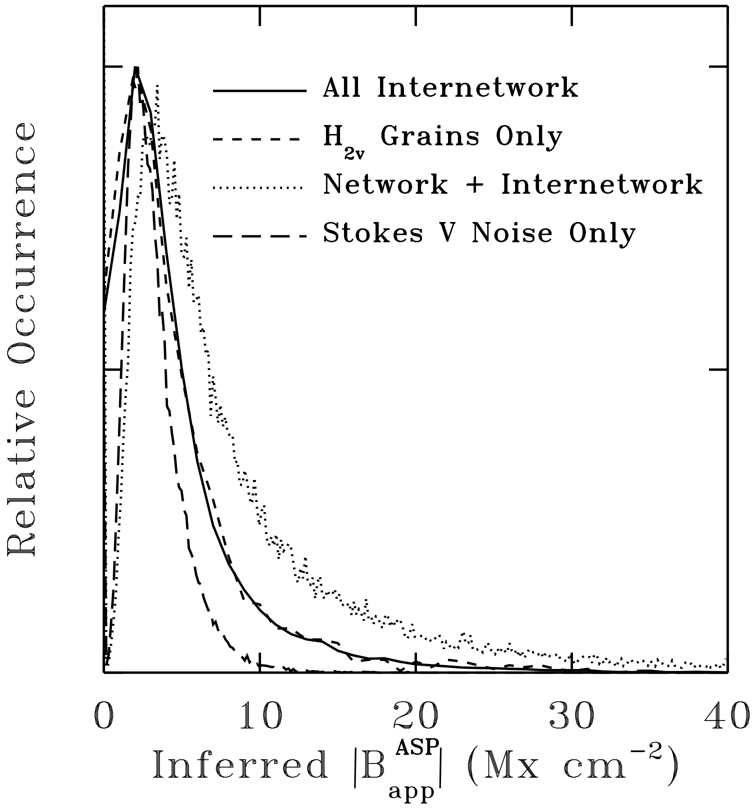

Figure 6. Histograms of the occurrence of weak internetwork fields measured with the Advanced Stokes Polarimeter at the NSO/Sacramento Peak Dunn Telescope. The quantity $|B^{\rm ASP}_{\rm app}|$ represents the apparent flux density derived from profile-integrated Stokes V measurements of the two Fe I 6302 Å lines. The solid curve specifies the flux density distribution for all of an internetwork area, whereas the similar dashed distribution holds for only those space-time locations where a Ca II H_{2V} grain appeared, as measured on simultaneous cospatial Ca II H spectrograms. The dotted curve includes strong-field network elements (they do not produce kilogauss apparent flux density because the magnetic elements are not resolved; the difference between the measured apparent flux density and the actual intrinsic field strength $B \approx 1400$ Gauss is largely a measure of spatial filling factor within the seeing-smeared and instrument-dependent resoluton element). The narrowest distribution is a noise estimate derived from the continuum which has no intrinsic Stokes V signal. Its peak defines the noise threshold of these data. From Lites et al. (1999).

1998). Much of the latter is hampered by insufficient solar area, temporal extent, spectral signal and line formation variety, but it is nevertheless clear that the internetwork scene is less clear in higher-formed UV lines than it is in H & K. This was already established from rocket data (Hoekzema et al. 1997). Part

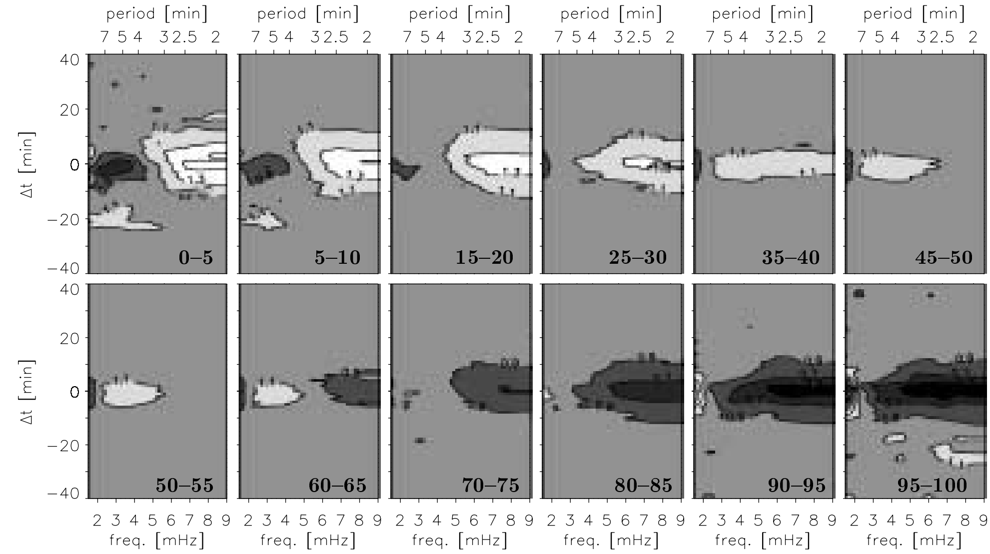

Figure 7. Contour maps measuring the amount of spatial correlation between the brightness of the granulation pattern and the occurrence of large oscillation amplitude, as functions of Fourier frequency (lower abscissae; corresponding periods along the tops) and time delay between brightness sampling and Fourier amplitude measurement (ordinate). The time delay is positive when brightness is sampled after Fourier amplitude. The panels divide the granulation brightness range into 5% bins, the top-left one being for image pixels in the darkest intergranular lanes, the bottom-right one for the brightest 5% of all pixels. Contour values exceeding unity (bright) imply that pixels with Fourier amplitude over twice the average, at the given frequency, are preferentially coaligned with pixels of the given brightness class. The contour value unity (grey) implies absence of systematic coalignment. Values below unity (dark) imply negative alignment (spatial avoidance). The bright blob at 2–3 min period in the upper-left panel implies that high-frequency waves are preferentially found at the very darkest features. From Hoekzema et al. (1998).

of the confusion may lie along the line of sight. The Ca II H_{2V} and K_{2V} grain emission senses the upcoming shocks just barely, when they are still quite weak and relatively regular, because the H & K line source functions are dominated by scattering in the higher layers where vertical shock interference produces more irregularity. It is also likely that high-frequency shock sequences interfere with the three-minute ones to a considerably larger extent than simulated by Carlsson & Stein (Ulmschneider, these proceedings). In addition, shock signatures are very much different between optically thick and optically thin line formation. Finally, it is likely that the shock trajectories are not radial as is assumed in 1D modelling or in pixel-by-pixel time sequence and temporal Fourier analyses. The frequent occurrence of K_{2V} grains in synchronized pairs suggests the presence of horizontally spreading disturbances.

The issue of whether internetwork grains betray specific pistons is yet open. A long-standing debate concerns the claim by Sivaraman & Livingston (1982) that K_{2V} grains correlate one-to-one with the presence of enhanced magnetic field (*e.g.,* Rutten & Uitenbroek 1991, Kneer & Von Uexkull 1993, Von Uexkuell & Kneer 1995, Steffens et al. 1996, Hofmann et al. 1996, Remling et al. 1996, Nindos & Zirin 1998, Wellstein et al. 1998). Recently, this claim has been tested directly by Lites et al. (1999) by repeating the measurements of Sivaraman & Livingston (1982) at higher precision and sensitivity. A key result is shown in Fig. 6. It indicates that, down to the measurement sensitivity of 3 $\mathrm{Mx\,cm^{-2}}$ in apparent flux density, there is no correlation between the presence of H_{2V} grains and enhanced Stokes V amplitude. A similar absence of significant correlation was found between H_{2V} grains and horizontal internetwork fields diagnosed from linear polarization (Lites et al. 1996). Thus, the occurrence of internetwork grains does not seem to depend on magnetism, apart from the rare persistent flashers.

It seems most likely that turbulent convection supplies the pistons that excite shock sequences producing bright internetwork grains. In particular, the grains may mark locations where "acoustic events" and "intergranular holes" follow on granular collapse (cf. Restaino et al. 1993; Rimmele et al. 1995; Rast 1995; Roudier et al. 1997; Hoekzema & Rutten 1998; Hoekzema et al. 1998; Goode et al. 1998). Figure 7 from Hoekzema et al. (1998) demonstrates in statistical fashion that high Fourier amplitudes in the 2–3 min period range are found preferentially above the darkest features in the granulation. These correspondence charts have been derived from white light images and therefore contain photospheric signal only. Combination of cospatial TRACE white light and near-UV image sequences will enable occurrence correlation between chromospheric internetwork grains and photospheric morphology and flow patterns down to granular scales, with sufficiently large data sets to assess the significance of any relation. The internetwork may so become the first domain in which chromospheric and photospheric dynamics are tied together in detail.

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