K_{2V} cell grains and chromospheric heating

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Abstract. The appearance of bright Ca II K_{2V} grains in the interiors of network cells on the solar surface is an intriguing phenomenon, rich in observational characteristics and possibly important in the energy budget of the quiet chromosphere. Unfortunately, their nature has eluded identification sofar. We discuss various scenarios and list observables which may verify or discard these, and we present predictions based on our own prejudices.

1. Introduction

Seen in the cores of the Ca II H&K resonance lines, the solar surface displays grainy emission patterns which primarily follow the surface distribution of strong-field magnetic flux (network and plages), and which together constitute a valuable proxy for magnetism in studies of cool-star activity. Inside the network cell interiors, however, there are tiny short-lived grains of enhanced emission. They brighten primarily in a narrow wavelength band on the violet side of the H_3 and K_3 line centers. These are the K_{2V} cell grains.

The grains have often been taken as direct manifestation of quiet-Sun chromospheric heating, most recently by Kalkofen (1989), but they have never been satisfactorily explained. This is regrettable since the grains supply a specific, well-defined phenomenon with much observational detail. They should provide valuable diagnostics of the dynamical interaction between photosphere and chromosphere—if we know what they are. We briefly discuss various possibilities here, and we present our own preferences. A more extended review, with many more references, will be published elsewhere.

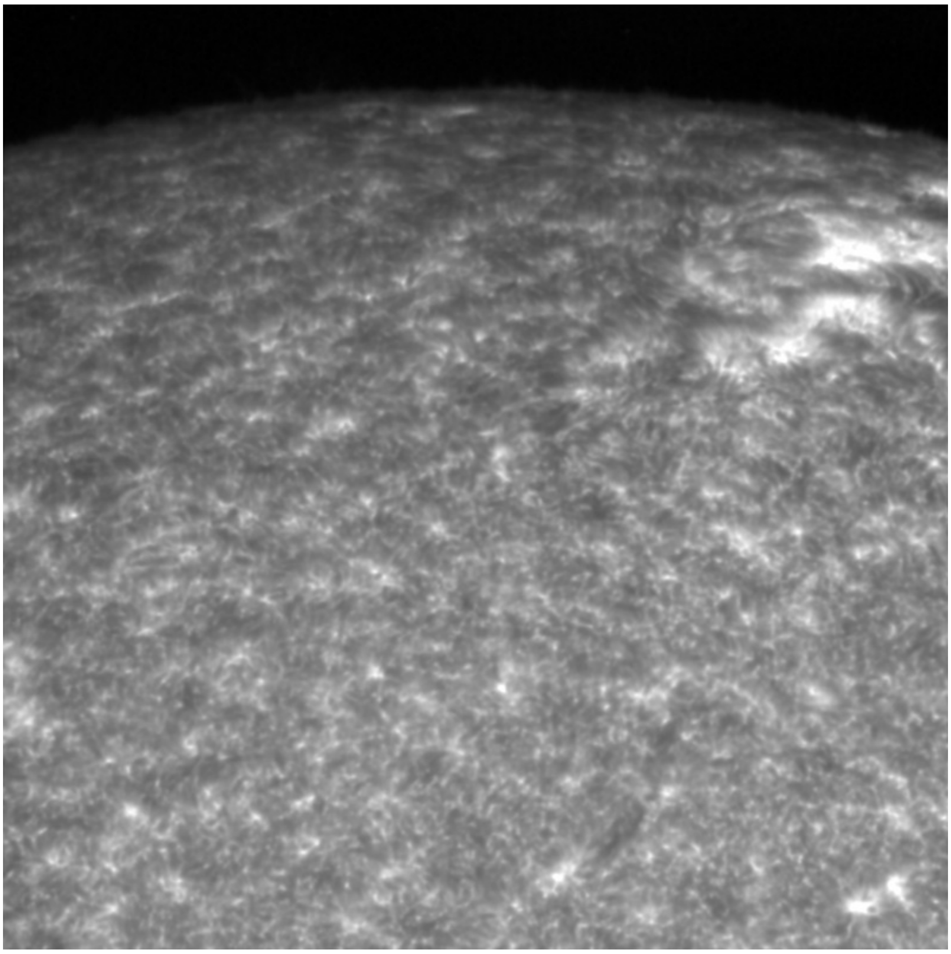

Figure 1: Negative image of the Sun taken in the K_{2V} wavelength just blueward of Ca II K line center. This is a part of what may be the best spectroheliogram ever taken, obtained by Bruce Gillespie with the East Auxiliary of the McMath Solar Telescope at Kitt Peak. K_{2V} cell grains are the tiny black dots (bright on the Sun) located in quiet cell interiors; the network is marked by elongated grey features. Courtesy of W.C. Livingston, National Solar Observatory.

2. Observations

We have no new K_{2V} observations to report here, although we (*i.e.* Brandt, Rutten, Shine and Trujillo-Bueno) hope to obtain some soon with LPARL equipment at the Swedish solar telescope on La Palma. However, there is an extensive observational literature, dating from the turn of the century onwards; the most comprehensive sets are the informative analyses of Sacramento Peak HIRKHAD spectrum sequences by Cram (1978) and by Cram and Damé (1983). The first paper addresses Ca II K behaviour in the Fourier domain, the second paper addresses K behaviour (actually for the H line) in the space-time measurement domain; the two papers are complementary.

Cram and Damé's paper demonstrates that the K_{2V} grains are small (1 Mm), short-lived (1 min) and repetitive (2–4 min intervals); they seem to have a location memory for at least 2–4 cycles and they are embedded in co-oscillating areas of 2–4 Mm size. They typically occur as part of a distinctive evolution pattern which also concerns the inner K-line wings. This is most clearly seen in the time-resolved spectra of Cram and Damé (e.g. frame 115 of their Fig. 4): a "bright disturbance" (Liu 1974) comes in from the wings and eats up the "dark whiskers" (Beckers and Artzner 1974) which extend out from line center; in the meantime, the K_3 core shifts redward. The K_{2V} flash typically occurs when the wing brightness reaches line center and K_3 reaches maximum redshift; it is followed by darkening of the wings and an abrupt blueshift of K_3.

Cram's Fourier analysis displays $k - \omega$ spectra for a photospheric Ni I line, Na D, Ca II 8542, Hα and various locations in Ca II K. The line shift power spectra show a progression with formation height from purely 5-min power to increased contribution from 3-min oscillations. The line intensity power spectra follow this pattern but with some delay; for example, Na D line shift behaves just as 8542 intensity. The K-line wings follow the same trend: at 3 Å from line center, the K intensity power spectrum equals the Ni I intensity power spectrum, at 0.9 Å the K intensity power specrum equals Na D intensity, and at K_{1V} the intensity power behaves as the Na D shift and the 8542 intensity. However, the Hα, K_2 and K_3 intensities do not follow this pattern. Hα, K_{2R} and K_3 have no 3-min power whereas the pattern predicts power like 8542 shift or Hα shift power; the K_{2V} intensity power spectrum resembles the Hα and K_3 line shift spectra rather than 8542 shift power. The typical spatial wavelength (derived by assuming circular symmetry on the solar surface) in Cram's power spectra is 8 Mm, in all diagrams (the same spatial scale as found in mesogranular motions). The intensity–shift phase difference is typically 90 degrees, up to the 8542 line. The same standing-wave signature is seen between K-wing intensity and shifts of superimposed blends (Liu, Beckers and Artzner).

In addition, there is a large literature on phenomena which presumably are related to the K_{2V} grains but for which the connection is not well established or not even studied at all: fine structure in the inner wings of H&K, 3-min oscillations of the Ca II IR lines, cell-interior dark grains and 3-min oscillations in Hα–0.5 Å, bright cell points in the 1600 Å continuum, intranetwork patches of weak magnetic field, bright and dark features seen in the CN 3888 Å bandhead, 3-min oscillations in IR continua and OH lines, quiet-sun C I blueshifted "jets" inferred from HRTS data, nonmagnetic "cool clouds" inferred from CO line limb darkening, *etc.* A comprehensive cell-interior picture should accommodate all these. For example, the pure 5-min power peak for the CO lines shown by Ayres in this meeting immediately puts their formation *below* the temperature minimum, whereas the pure 3-min oscillation of the 1600 Å bright points immediately puts them well *above* the temperature minimum. Harvey's seismological use of the K-line wings demonstrates that these contain more than granular and reversed granular fine structure alone; higher up, the Hα–0.5 Å oscillations resemble the Ca II 8452 Å Doppler behaviour closely. All of these phenomena must be tied together.

3. Ingredients

The above observations and our PRD line formation modeling (which we will report elsewhere) imply that any K_{2V} scenario must contain the following ingredients:
(i)—K_3 redshift. The K_3 layer has a sawtooth Dopplershift motion which reaches a sizable (5–10 km/s) redshift at the K_{2V} flash moment. The redward (down) excursion is larger and slower than the blueward (up) excursion.
(ii)—Heating of the K_2 layer. This is evident as wing brightening. It is not clear whether this brightening, although it is often seen to progress from the line wings to line center, corresponds to an upward propagating temperature enhancement or not; the progression may be apparent, due to increasing phase retardation by decreasing radiation losses in a standing adiabatic-like wave (Deubner, private communication). Indeed, Cram's phase spectra and the K-wing blends indicate standing waves; note also that the K-line wings themselves are dominant radiation sinks at their own formation height.
(iii)—Oscillations. The wing brightenings and the K_3 Doppler maneuvers are both part of oscillatory patterns; for K_3 these are best depicted by Cram and Damé's V/R space-time diagram. The two patterns are not necessarily the same, and the large variations in K_{2V} grain behaviour may mark interference between different systems. However, bright K_{2V} grains and dark K_{2R} grains are always part of spatially more extended oscillation patterns. These cover *all* of a quiet-cell interior, but not all of them contain K_{2V} grains in their bright phase, at least not all of the time.

Together, these ingredients imply that oscillations play an important role but that something drastic happens between the K_2 and K_3 layers. The core opacity sits redward when the K_{2V} flash occurs; at that moment, K_{2V} sits in a more or less stationary layer with small overlying opacity.

There are also questionable ingredients:
(i)—K_3 blueshifts. The observations rule out the often-invoked option of letting

the K_{2V} flash be blueshifted line-center emission, because K_3 blue-shifts *after* the flash.

(ii)—Strong-field fluxtubes. The small size of the K_{2V} grains and their apparent location memory have often been explained as due to fluxtubes. But the grains are part of larger, ubiquitous oscillation patterns, present all over the sun *except* where it is active.

(iii)—Weak intranetwork fields. Sivaraman (these proceedings) has observed a one-to-one correlation between K_{2V} grains and magnetic features in cell interiors which has never been confirmed.

(iv)—Cavities. The 3-min oscillatory behaviour has often been attributed to a chromospheric cavity, first by Mein and coworkers. But they may also be free oscillations, having 3-min character because lower frequencies are cut off in the temperature minimum. Any kick to the photosphere may produce them (Gouttebroze and Leibacher 1980, Fleck and Schmitz, these proceedings; Steffen *et al.*, these proceedings).

(v)—Pistons. The oscillations seem ubiquitous but the K_{2V} grains less so. Perhaps the former are excited by piston action which is reflected more directly by the latter. There are many piston candidates: the accidental wave trains of the 5-min *p*-mode interference patterns, the upthrust of large granules or their central downflow when they explode, vortices where the mesogranular flows converge, collapsing flux tubes, flux tube wave modes, small-loop reconnection, stand-off shocks in siphon flows, take your pick! (In 1900 Jewell suggested infalling meteorites.)

4. Scenarios

Let us now sketch various K_{2V} scenarios:

(i)—Fluxtubes plus fluxtube waves. Do K_{2V} grains mark strong-field fluxtubes in cell interiors? The advantages are that fluxtubes can easily supply small hot spots, a good location memory and many types of wave modes. But why should fluxtubes sit nicely at the center of ubiquitous oscillation patterns? Also, the presence of strong-field fluxtubes in cell interiors is in general highly questionable. Concentrations of intrinsically weak field may exist but do not provide these properties. Also, the oscillation properties of cell interiors differ markedly from those of the network boundaries (Deubner and Fleck 1990)—the latter do consist of strong-field tubes but have less 3-min power. Neither do they produce K_{2V} grains.

(ii)—Pure oscillations. Are K_{2V} grains just another aspect of global oscillations, driven by subsurface turbulent convection? If so, the ubiquitous oscillatory nature is taken care of. But it isn't clear whether 4 Mm wave humps can lead to such tiny emission features without further ado, and oscillation interference patterns have spatial location memory for only a few cycles. Only a few oscillation sites produce K_{2V} flashes per cycle, which asks for an independent selection mechanism.

(iii)—Piston-incited waves. Pistons can provide spatial patterns and location memories. The 5-min *p*-mode interference patterns produce 3–5 cycle wavetrains, thus

pistons with 30 min memory, of locations that are about mesogranularly spaced. Exploding granules are concentrated in mesogranular divergence centers and they therefore provide mesogranular signature too. Such pistons can also produce small geometrical extent and sharp localization if the excited wave reaches sufficient steepening only directly above the piston. A problem is that all wave modeling (as Gouttebroze and Leibacher's) produces K_{2R} bright grains in about equal measure, in conflict with the rare occurrence of actual K_{2R} bright grains. However, the observations suggest that the K_3 layer falls down on a shock-heated layer where the K_{2V} flash is formed. Computations of steepened short period waves do show such behaviour, but only after multiple cycles have passed. Can it be that the K_{2V} grains mark sites where backfalling matter from a previous cycle hits the next upcoming one, flashing only after a well-developed wave train has gone through enough cycles?

5. Observables

These various scenarios can be tested observationally. A prime issue is the spatial behaviour of K_{2V} grains. What is their location stability? Do they coincide with magnetic elements? Or with flow elements? One should look for co-spatiality of K_{2V} grains with filigree and "network bright points" at the photospheric level to prove the fluxtube scenario, and one should look for co-spatiality between K_{2V} grains and photospheric 5-min wavetrains, exploding granules, vortices *etc.* to find pistons. If the grain location memories are very long (as has been claimed) such spatial correlation should easily become evident.

It will also be worthwhile to study the ridge and phase structure of the cell-interior $k - \omega$ domain using the K_{2V}/K_{2R} intensity ratio as a proxy for K_3 Dopplershift. Wavetrain-comparison between the V/R signal and lines formed lower down (such as Ca II 8542 Å and Hα–0.5 Å) may demonstrate the wave steepening directly.

Fast CCD registration, active mirror image motion correction, autocorrelation tracking, fast tunable filter cycling, spectrograph area scanning and other new techniques now permit the taking of sufficiently long sequences of sufficient resolution containing sufficient complementary diagnostics that the K_{2V} problem should be solved soon.

6. Prediction

Having optimistically predicted that the solution will come soon, we take an unusual step and predict also what that solution will be. We begin by discarding magnetism as an ingredient: we claim that the K_{2V} phenomenon is purely hydrodynamical. It consists of free-oscillating 3-min waves, excited in the photosphere, which become dominant above the temperature minimum and start propagating higher up, steepening and causing shock heating at the K_2 (and 1600 Å) level, but only when the higher layers seen in K_3 fall back down onto the next one, and only directly above a piston.

What piston kicks? We hesitate between 5-min wavetrains of the *p*-mode interference pattern and exploding granules. The former option seems more likely but the latter would make the K_{2V} grains much more interesting: they should then reflect the horizontal flow patterns in which their pistons take part whereas the 5-min wavetrains are just happenstance *p*-mode interference, without much spatial interest. Conforming to a principle formulated earlier by one of us (Rutten 1990), we choose the more informative option (even though we think it less likely) and predict that K_{2V} grains mark the mesogranular divergence centers just as exploding granules do.

7. Conclusion

Do K_{2V} cell grains heat the quiet chromosphere? It has often been suggested, and it may well be so; they do contribute to the energy budget if they are indeed due to photospherically-excited waves that propagate up and shock downward as we believe. However, we think the issue irrelevant until the full budget is known; its evaluation requires more than the identification of just one phenomenon. For example, the CO cool-cloud issue must first be decided as well. Again, a more holistic picture addressing all diagnostics listed above is required.

Our hopeful conjecture that the cell grains outline photospheric mesogranular flow fields with high spatial precision should, if proven correct, make them valuable diagnostics of the hydrodynamical patterns in and below the solar atmosphere, just as the network boundary and plage calcium “emissions” are valuable spatial indicators for magnetic surface patterns. The solar surface patterns and the stellar amplitudes of dynamo activity are more easily measured from chromospheric calcium emission than from magnetic signatures; our hope is that the cell grains (and possibly the K_2 V/R asymmetry in spatially averaged spectra) furnish similarly easy diagnostics of surface flows and subsurface convection. Thus, the major interest in the K_{2V} cell grains may lie not so much in their role as heaters in the quiet chromosphere but rather in their usefulness as measuring instruments—just as the calcium cores do not only provide radiative cooling to solar fluxtubes but also, and more valuably, cool-star magnetometers to terrestrial observers.

References

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Discussion

F.-L. Deubner: First, I agree with your scenario in the higher atmosphere if it gives downward propagation of energy. Second, the Cram and Damé space-time diagram of the V/R brightness ratio is very similar to phase diagrams of the 5-min oscillations. This similarity does not support the notion of "fixed" pistons deeper down.

Answer: K_3 shows faster downdrafts than updrafts and the stand-off shock caused by the downfalling K_3 layer in our scenario may well provide net downward propagation. Yes, the patterns in their diagram are very oscillatory in character outside the network boundaries: K_3 oscillates everywhere. But the K_{2V} flashes do not occur everywhere in tandem: there are many places where the V/R ratio is bright only because K_{2R} is extra dark, *i.e.* where K_3 is redshifted on to K_{2R} without accompanying K_{2V} flash. An extra ingredient seems necessary, perhaps a strong initial piston stroke.

J. Hollweg: Your scenario, especially if you tie in the C I jets, reminds me of the "rebound shock mechanism" that Sterling and I developed for spicules. Do you think there is a connection?

Answer: The cell grains have nothing to do with spicules but the mechanism may well be of that sort—similar hydrodynamics. It will be of interest to study co-spatiality between C I jets and 1600 Å bright points in HRTS data, accounting for phase delay between these phenomena, and if there is co-spatiality, to study the phase delays. To my knowledge, this hasn't been done.

T.R. Ayres: Has the emission in these grains to do with the basal flux?

Answer: I don't know, but Skumanich *et al.* (1984, *Ap. J.* **282**, 776) estimate their contribution to the Sun-as-a-star flux as negligible.

L. Damé: Recent work by Martič and myself supports your suggestion of a mesogranular piston. At the height of the temperature minimum we find stable brightenings of mesoscale dimension (10 arcsec) and 180 s periodicity which correlate with the occurrence of bright points.