Astron. Astrophys. 335, 323–328 (1998)

ASTRONOMY
AND
ASTROPHYSICS

Oscillations of the Sun's chromosphere

VIII. Horizontal motions of Ca II K bright points

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Received 24 November 1997 / Accepted 24 March 1998

Abstract. We present a re-analysis of a time series of solar disc centre Ca II K_{2v} filtergrams taken with the Vacuum Tower Telescope at the Observatorio del Teide/Tenerife. We concentrate on the measurements of proper motions of K grains in the internetwork regions and of bright points in the chromospheric network. For the K grains we find horizontal velocities of 2–15 km s^{-1}, values much lower than those deduced by Steffens et al. (1996) from a smaller sample, analyzed differently. In accord with our earlier conclusion from k-ω diagrams (Kneer & von Uexküll 1993) and with numerical simulations by Carlsson & Stein (1997) high-frequency (pseudo-) p-modes can viably explain the K grains. Yet, the rareness of the K grains may indicate a connection to magnetic fields. The proper motions of the network bright points are non-periodic, very impulsive, with velocities of 7–10 km s^{-1}. Estimating the energy flux if these motions are magnetic kink waves (cf. Choudhuri et al. 1993, Muller et al. 1994), we find it sufficient to heat the solar corona, but too small to cover the radiative losses of the chromospheric network.

Key words: Sun: chromosphere – Sun: oscillations

1. Introduction

This study deals with the chromosphere of the quiet Sun and its spatio-temporal variation. Using a Lyot-type filter tuned to the Ca II K line one sees a wealth of fine structure. We discriminate between the chromospheric network (henceforth cell boundaries, CB) and the interior of the network cells (henceforth cell interior, CI).

The CBs are related to small-scale kilogauss magnetic flux tubes advected by the supergranular flow. They retain their identity for approximately 1 day. They consist of conglomerates of bright points (BPs) with life times of tens of minutes to a few hours.

In the CI point-like brightenings are conspicuous. Following a widespread custom, we call them K grains (Beckers 1964). They are quasi-periodic with a few (2–5) brightenings at intervals between 140 s and 250 s. Sometimes just one brightening occurs. K grains are thus rather short-lived phenomena. The bright phase lasts 45–60 s, rarely longer. During maximum they attain the intensity of the BPs at CB. We refer to our previous work, especially to Paper VII of this series (von Uexküll & Kneer 1995), for this behaviour of K grains and to the review by Rutten & Uitenbroek (1991) for an extensive description of their properties.

Both CI and CB require non-radiative energy supply for the emission in excess of the output from an atmosphere in radiative equilibrium. However, they behave very differently in time (cf. Paper VII), and it is widely accepted that the magnetic field causes the difference.

For the K grains in CI, analytical work as well as numerical simulations suggest that the solar atmosphere reacts sensitively to perturbations. Waves with frequencies preferentially near the acoustic cutoff (period approximately 200 s in the solar atmosphere) are easily excited (Rammacher & Ulmschneider 1992, Fleck & Schmitz 1993, Kalkofen et al. 1994). Carlsson & Stein (1997, henceforth CS) published results from one-dimensional numerical simulations. The dynamic behaviour in the simulations, based on Doppler shifts in a photospheric line observed simultaneously with the H line (Lites et al. 1993), reproduces the observed Ca H line spectroscopic features and their temporal evolution in CI. It thus appears that K grains have been explained by the CS calculations as a consequence of the photospheric wave field.

The horizontal proper motions of K grains have been measured by Steffens et al. (1996) who found velocities between 30 km s^{-1} and 80 km s^{-1} with an average of about 50 km s^{-1}. This finding is disturbing because, during their brightness phase of 45–60 s, K grains would then travel horizontally of the order of 3 000 km, which is about a factor 3 larger than the vertical distance to the photospheric driving in the CS calculations. Before discussing in depth the implications – we shall expand on this point below – it is worth while to re-measure the horizontal motions of K grains. We thus shall present new results on K grain motions.

With regard to the dynamics of the CB, from the analysis of a spectroscopic time series, Lites et al. (1993) obtained velocity oscillations in Ca II H with low frequencies, i.e. periods of 400 s, 550 s, and 1100 s. With material of high statistical signifi-

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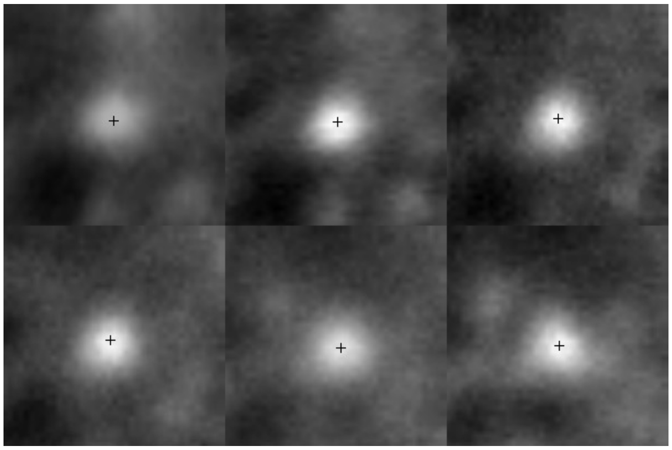

Fig. 1. Sequence of K grain pictures at 15 s cadence, from left to right, starting with the upper row. The average horizontal velocity is 1.7 $\mathrm{km\,s^{-1}}$. The size of the frames is $7\farcs2 \times 7\farcs2$.

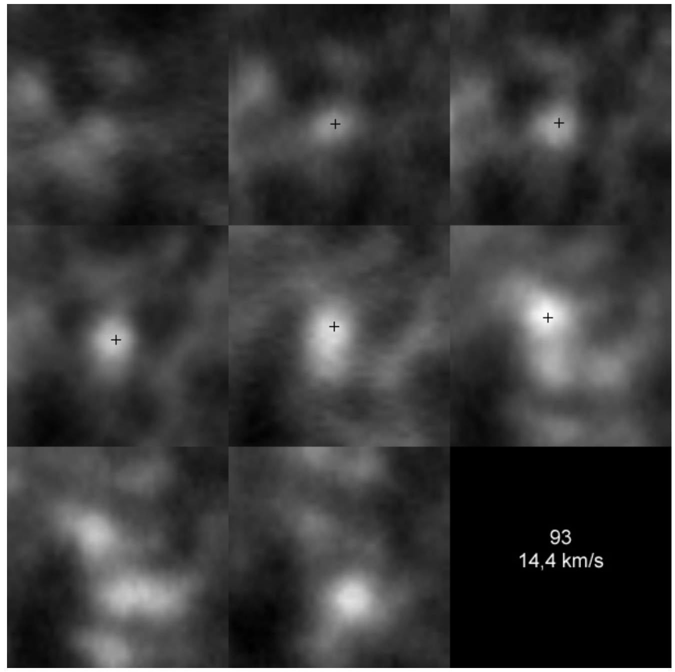

Fig. 2. Example of K grain time sequence with problematic definition of the grain position towards the end. The sequence goes row by row starting at the upper left corner, with 15 s time step, $7\farcs2 \times 7\farcs2$ frame size.

cance and using Hα spectrograms as well as filtergrams in Hα, Mg b_2, and Ca K as diagnostics, Kneer & von Uexküll (1986), von Uexküll et al. (1989), and Kneer & von Uexküll (1993) found no indication of periodic behaviour of CB at low frequencies and attributed the power there to stochastic processes. It is thus important to clarify whether the BPs at CB move periodically or randomly, if at all, and what their horizontal velocity is. von Uexküll et al. (1989) estimated the energy supply from the network velocities inferred from Hα and found it sufficient to cope with the chromospheric radiative losses. It was pointed out later by Choudhuri et al. (1993) from theoretical considerations and by Muller et al. (1994), who measured proper motions of photospheric network bright points, that the motion of BPs is relevant for coronal heating by kink waves. Thus, while measuring horizontal motions of K grains in CI, we can do the same on BPs at CB with the identical set of observations.

2. Observations and data analysis

We used part of the observations which were described in Paper VII and which were obtained with the Vacuum Tower Telescope at the Observatorio del Teide/Tenerife. We selected a 45 min time span with exceptionally good seeing out of a 2 h time sequence of Ca K filtergrams from quiet Sun disc centre. The filter was tuned to the K_{2v} spectral feature and its bandwidth was 0.3 Å. The time step was 15 s. The image scale on the Thomson TH 31156 CCD detector was $0\farcs18$/pixel.

The usual pre-reduction of the data was performed: average dark frames were subtracted; bad-pixel signals were eliminated by means of a median filter; the resulting images were divided by the gain table which was obtained from defocussed images. To eliminate fluctuations of the sky transparency the images were normalized by their average count rates.

Image displacements due to image motion and to guiding errors were eliminated to sub-pixel accuracy. For this, the images at each time were smoothed with a median filter of $1\farcs8$ width which eliminates the short-lived fine structure. They were then shifted with bilinear interpolation to maximum correlation with the time averaged frame. The finally remaining field of view was $140'' \times 140''$.

The shift to maximum correlation on the whole field of view does not correct for higher order seeing terms such as distortion. An image destretching applied to a mosaic of small subframes is not appropriate since it corrects for displacements to be measured as proper motions. Thus an additional correlation technique was applied to subfields of approximately $25'' \times 25''$, but only to CB regions. The results for BP proper motion with and without this final correction were very similar. Likewise, the results below show that the K grains possess rather slow horizontal motions. This gives some confidence that image distortions have little, if any, influence on the determination of proper motions.

After these procedures, the horizontal velocities were determined by following the spatial position of the bright features during the time when they could be indentified. K grains were traced during about 60 s, i.e. during their brightness phase. Occasionally, repetitive K grains were traced; those resulted in velocities similar to the ones during their first appearance. Network BPs could be followed for time spans of 5–23 min, which are the time spans over which the BPs could be identified unambigously.

For both BPs in CB and K grains in CI, one often faces the problem of identifying the feature after a while. CB regions consist of extended conglomerates of BPs which change their shape in a short time. This may likely be caused by changes of the magnetic field structure as demonstrated, e.g., by Volkmer et al. (1995) and also deduced from G band (4305 Å) observations by Löfdahl (1996) and Berger & Title (1996). Besides, BPs may split from other BPs and coalesce again after a few min. K grains in the CI may fade away while nearby a separate brightening appears. At some instant and with insufficient spatial resolution, the two may produce one broad feature, and finally only the younger structure remains. In such cases, taking the centre of gravity of the bright structure as done by Steffens et al. (1996) for the velocity determination yields very different results as when the motion of the single features is measured. We will show an example below.

Due to these difficulties we have chosen to trace the bright features manually and only during times when they definitely exhibit a bright core whose centre was defined as the position. Following a feature over approximately 60 s and admitting an accuracy of position of ± 1 pixel ($\widehat{=}0\overset{\prime\prime}{.}18$) gives an accuracy of the average velocity of ± 3.0 km s^{-1}. For well defined features lasting longer the accuracy may be higher, ± 2.0 km s^{-1}.

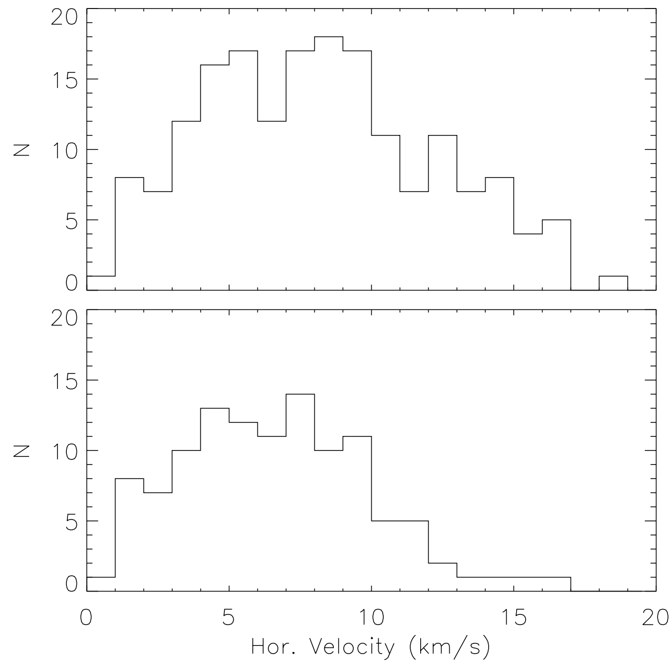

Fig. 3. Distributions of horizontal velocities of K grains. Upper panel: 182 K grains with unambiguously determinable positions; lower panel: 113 K grains with well defined positions.

3. Results

3.1. K grains in cell interior

Fig. 1 gives an example of an isolated K grain that could well be followed for 75 sec. Its FWHM at maximum brightness is about $1\overset{\prime\prime}{.}2$ and its velocity deduced from the core position amounts to 1.7 km s^{-1}. This is one of many examples with low velocity (cf. also Fig. 3), much lower than the values given by Steffens et al. (1996), which demonstrates that image distortion was minute. Otherwise such small values would not have been measured, on average.

Fig. 2 shows the temporal evolution of a K grain with more complex ambient structuring than in Fig. 1. The grain starts its brightness phase at frame No. 2. At frame No. 5 (centre frame of Fig. 2), two neighbouring features develop. At frame No. 6, the 'old' grain still exhibits a definite roundish, bright core. Yet using the centre of gravity of brightness would give a large, very likely misleading proper motion. At frame No. 7, the brightness distribution is too washed out to allow a definition of the core position. The proper motion of 14.4 km s^{-1} measured here is still much lower than the values given by Steffens et al. (1996).

Altogether 182 K grains whose positions could unambiguously be followed were selected. Fig. 3 gives in the upper panel the distribution of their horizontal velocities. The average velocity is 8.4 km s^{-1}. Selecting further among these grains the ones with very well defined positions we retained 113 grains whose velocity distribution is shown in the lower panel of Fig. 3. Here, the average horizontal velocity is 6.6 km s^{-1}. One notices that mainly the larger velocities have dropped from the distribution in the last selection process. In any case, we find very small K grain proper motions, down to 2 km s^{-1}, with the average a factor of 6–8 smaller than Steffens et al. (1996). We note, without illustrating, that position measurements from repetitive K grains give nearly identical velocities in all brightness pulses.

3.2. Bright points in the network

On grounds described above, isolated BPs at CB are rare in our limited field of view. Only 11 BPs were found whose positions could be traced for some time. We took running means over 60 s of the positions and determined the horizontal velocities for each time step from the distances which the BPs moved within the 60 s interval. Apparently, the BPs exhibit random motions as demonstrated in Fig. 4. This is very similar to the motions of photospheric facular points derived from an excellent white light time sequence by Muller et al. (1994). The longer the time interval taken for the running mean position the smaller the proper motion. The BPs move to and fro and may end at their starting position. A periodicity of motion cannot be seen in Fig. 4.

Fig. 5 depicts the temporal development of the horizontal velocity of a BP at CB. Velocities as large as 7 km s^{-1} may occur. Also noteworthy and of relevance for the transport of energy into the corona are the changes of velocity on short time scales, i.e., the high accelerations (cf. Choudhuri et al. 1993, Muller et al. 1994).

Finally, Fig. 6 gives the velocity distribution at each time step for the 11 BPs, after the above smoothing with running means over 60 s. Only a few cases were found with velocities larger than 10 km s^{-1}. The average velocity here is 4.1 km s^{-1}.

4. Discussion

4.1. K grains in cell interior

Carlsson & Stein (CS, 1997) state in their conclusion that the "bright grains are produced primarily by waves near and slightly

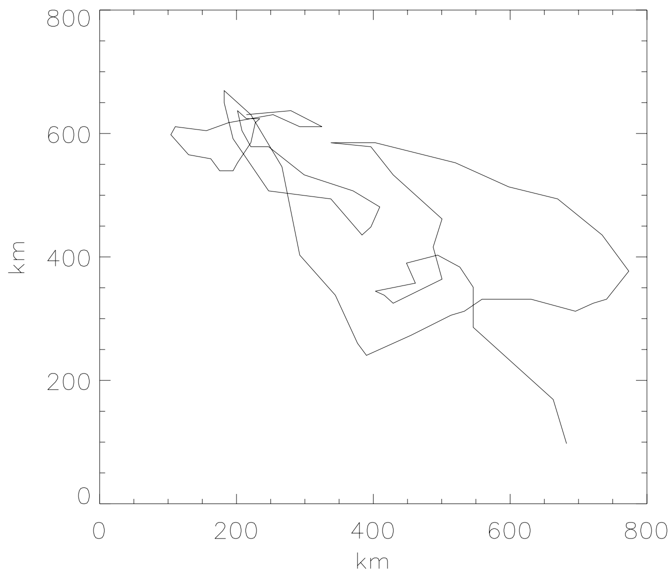

Fig. 4. Positions of a network bright point (BP) at 15 s cadence. The positions are running means over 60 s intervals.

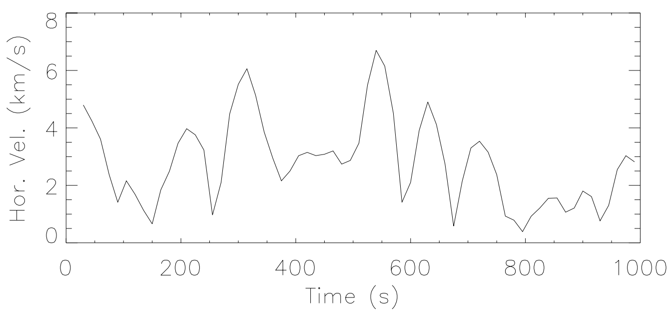

Fig. 5. Time development of horizontal velocity of a network bright point (BP) after taking running means of the positions over 60 s. The velocities are derived from the distances which the BP moves within the 60 s time interval.

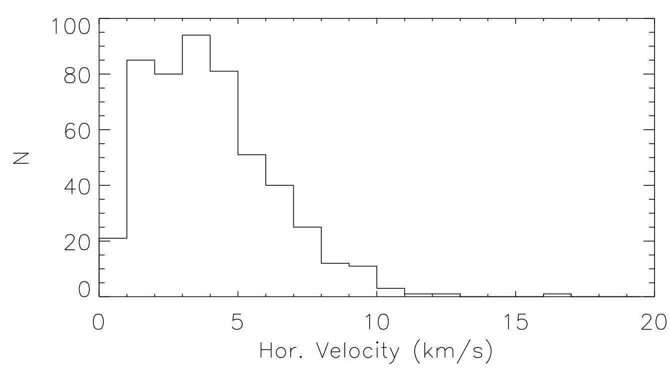

Fig. 6. Distribution of horizontal velocities of network bright points (BPs).

above the acoustic cutoff frequency", and that "the average (5 min) trapped p-mode oscillations are not the source of the grains". We remind the reader at this point that near and above the acoustic cutoff frequency one sees substantial oscillatory power ordered in p-modes (cf. Kneer & von Uexküll 1993, or Paper VII Fig. 8, and Ronan 1992). These may either be purely propagating pseudo-p-modes (Kumar & Lu 1991), or acoustic waves partially reflected at the transition zone, thus partially trapped p-modes, as indicated by their high vertical phase velocity (e.g., Kulaczewski 1992, see also Balmforth & Gough 1990). Additionally, according to Carlsson & Stein (1994), a "chromospheric" rise of the average temperature in the layers forming the K_{2v} spectral feature is neither produced in the simulations nor needed to reproduce the observations. The K_{2v} brightening occurs during the phases of high temperatures produced in upward propagating shocks. They are not the signature of a 3 min eigen-mode of the chromosphere proper.

Steffens et al. (1996) presented measurements of horizontal velocities of K grains of about 50 km s^{-1}. Taking this as a phase velocity, $v_{\rm ph}$, of a quasi-periodic phenomenon with a period of 180 s one arrives at wavenumber $k_{\rm h} = \omega/v_{\rm ph} \approx 0.07\,{\rm Mm}^{-1}$, or degree $l \approx 500$. The corresponding wavelength is 9 Mm. Furthermore, Hofmann et al. (1996) presented phase measurements and argued that "there is no need to distinguish carefully between p-mode oscillations and K grains – K grains are just one observational aspect of the p-modes". This agrees with our earlier proposition (Kneer & von Uexküll 1993) based on power spectra in the k-ω plane. Indeed, there is substantial oscillatory power around and above the acoustic cutoff frequency ($\nu_{\rm ac} \approx$ 5 mHz, $\omega_{\rm ac} \approx$ 0.031 s^{-1}) in the (pseudo-)p-modes. Thus, this picture of K grain excitation by medium degree (l) p-modes is appealing.

In contrast, however, the present study gives much lower horizontal velocities. A phase velocity of 6.6 km s^{-1} and a period of 180 s would place the K grains at $k_{\rm h} \approx 5.3$ Mm^{-1} or a wavelength of 1.2 Mm, which is at the high horizontal wavenumber tail of the f-mode (or surface gravity mode, cf. Fig. 8 in Paper VII). Yet we also find lower velocities which require still higher wavenumbers at the same frequency.

What then are K grains? Can we reconcile our finding with the CS picture above and with the medium degree p-mode waves near the acoustic cutoff frequency? Why are K grains so small, from less than $1''$ to $2''$–$3''$ compared to the wavelength of the exciting oscillations? Why do we find so much smaller horizontal velocities than the phase velocities of the medium-l p-modes would require and found by Steffens et al. (1996)?

Possibly, our observational results may also be interpreted as p-modes which form shocks: Whether shocks are formed depends on the pre-conditioning of the atmosphere which is much influenced by small-scale dynamics and interference, which makes K grains small-scale as well. We find small K grain velocities because the pre-conditioning is local and does not move horizontally with the phase velocity of the p-modes. The velocities given by Steffens et al. (1996) may likely refer to those few cases where conditions allow shocks to form almost simultaneously at adjacent positions, possibly excited by the same p-mode wave train. Presumably, Fig. 2 above shows an example of such a case.

A further observational fact is the rareness of K grains (cf. Paper VII). Truly bright grains with strong intensity oscillations, such as in Fig. 2 of Paper VII, occur only about 10% of the time.

This was confirmed by Steffens et al. (1996) who measured the intensity contribution of K grains to the total internetwork intensity and found it to be only 9%. In addition, some internetwork areas stay inert for hours with respect to the bright grains. Based on these K grain properties and on observations by Sivaraman & Livingston (1982), Kalkofen (1996) concludes that K grains could be related to weak internetwork magnetic fields which are buffeted by granular motion. It is worth repeating the observational test of such a K grain – magnetic field relation with high precision. Yet in this picture, the horizontal K grain velocities are expected to be low.

4.2. Bright points in the network

The *horizontal* velocities found here for K_{2v} BPs at CB are similar to the 4 $\mathrm{km\,s^{-1}}$ *vertical* velocities of Hα structures at CB given by von Uexküll et al. (1989). In this earlier study we estimated that these random motions, when applied to magnetic fields, give sufficient energy to heat the chromosphere and the corona via mechanisms of magnetic energy release suggested by van Ballegooijen (1986) and Parker (1987). The similarity of the Hα and K_{2v} velocities at CB confirmes our earlier estimate.

A further outcome of the proper motions of the BPs could be the excitation of kink waves in the related magnetic flux tubes (Choudhuri et al. 1993, Muller et al. 1994). The velocities in the present study are larger than the photospheric BP velocities found by Muller et al. (1994). This may be an effect of geometrical height, but certainly needs a discussion within magnetic field dynamics which is beyond the scope of this observational investigation. On the basis of the theoretical analysis by Choudhuri et al. (1993), Muller et al. (1994) estimated from the photospheric velocities the energy flux to the corona by means of kink waves. We can follow the same procedure, scaling the magnetic field, filling factor, and density to the height of the K_{2v} forming atmospheric layer (≈ 1100 km as a lower limit, cf. CS) and applying our measured velocities and time scales.

The energy supply per pulse and magnetic flux tube is (cf. Choudhuri et al. 1993, Muller et al. 1994)

$$E \;=\; 10^{26} C \left(\frac{\rho_0}{10^{-7}\mathrm{g\,cm^{-3}}}\right)\left(\frac{A_0}{10^5\mathrm{km}^2}\right) \times \left(\frac{v_0}{1\,\mathrm{km\,s^{-1}}}\right)^2 \left(\frac{H}{250\,\mathrm{km}}\right)\left(\frac{F(\lambda)}{\lambda^2}\right)\mathrm{erg}\,. \qquad (1)$$

Here, the constant $C = 6.5$ accounts for the total energy supply. As an upper limit, we take the scale height H in an isothermal atmosphere of 7000 K, which gives approximately 150 km. With this and a photospheric density $\rho_{\rm ph} = 3\,10^{-7}\mathrm{g\,cm^{-3}}$, we have $\rho_0 = \rho_{\rm ph}\exp(-1100/150)$. The area A_0 of the magnetic flux tubes is derived from flux conservation and a constant plasma $\beta = 8\pi p/B^2$ (≈ 0.5) which gives $A_0 = A_{\rm ph}\exp(1100/300)$ with $A_{\rm ph} = 0.18\,10^5$ km^2 from Muller et al. (1994). For v_0 we take 6 $\mathrm{km\,s^{-1}}$ and for the dimensionless parameter $\lambda = v_0/(\omega_{\rm c}L)$ = 2.0, where $\omega_{\rm c}$ is a cutoff frequency $\approx 10^{-2}\,\mathrm{s^{-1}}$ and the length scale $L = v\Delta t$ ($v = 3$ $\mathrm{km\,s^{-1}}$ the average velocity during a pulse and $\Delta t \approx 100$ s the pulse duration from Fig. 5). The function $F(\lambda)$ is given by Fig. 6 in Choudhuri et al. (1993). We extrapolate it to λ = 2.0. With these values, Eq. (1) yields $E \approx 2.3\,10^{25}$ erg per pulse. Adopting from Muller et al. $N_{\rm BP} = 200$ network bright points in a $100'' \times 100''$ area and from Fig. 5 approximately $N_{\rm P} = 5$ pulses per 1 000 s, one arrives at an energy flux

$$F \;=\; E\left(\frac{N_{\rm P}}{1\,000}\right)\left(\frac{N_{\rm BP}}{100''\times 100''}\right) \approx 4.4\,10^5\,\mathrm{erg\,cm^{-2}s^{-1}} = 440\,\mathrm{W\,m^{-2}}\,. \qquad (2)$$

This is smaller, but of similar order as the flux estimated by Muller et al. ($\approx 2\,000\,\mathrm{W\,m^{-2}}$). It may suffice to heat the corona, but it falls short of covering the radiative losses of the chromospheric network, for which one estimates 1.5–2.0 10^4 $\mathrm{W\,m^{-2}}$ (cf. von Uexküll et al. 1989). It is tempting to conclude that the difference between the energy fluxes estimated from the photospheric BPs and Ca K network BPs accounts for the chromospheric radiative losses. However, the accuracy of the estimates is not sufficient to support such a statement.

5. Conclusion

As in our earlier studies, it proved valuable to analyse time sequences of filtergrams. The velocities of proper motion measured from 182 K grains in the chromospheric cell interiors are 2–15 $\mathrm{km\,s^{-1}}$. On average, these are a factor of 6–8 smaller than the values given by Steffens et al. (1996) using a different type of analysis. We find the low values still compatible with an excitation of the K grains by medium degree ($l \approx 500$) p-modes near the acoustic cutoff frequency, such as suggested by the (successful, though one-dimensinal) hydrodynamic numerical simulations by Carlsson & Stein (1997). Yet based on the observed rareness of K grains and the low K grain activity of large parts of the internetwork area, a magnetic-granular interacton is still a viable possibility (Sivaraman & Livingston 1982, Kalkofen 1996). It will be worthwhile, albeit difficult, to definitely clarify via observation the rôle of the internetwork magnetic fields.

The proper motions of K_{2v} network bright points are nonperiodic, their velocities are of the order of 4 $\mathrm{km\,s^{-1}}$ with maximum speeds of 7 $\mathrm{km\,s^{-1}}$. These values are larger by about a factor of 2 than the photospheric bright point velocities given by Muller et al (1994). Guided by these authors and by Choudhuri et al. (1993), we estimated the energy flux of magnetic kink waves which may be produced by horizontal, pulse-like motions. It comes out smaller by about a factor of 4 than the values given by Muller et al. (1994), and we find that it is insufficient to cover the radiative losses in the chromospheric network. As for the K grains, it is important to find out by observation the connection between photospheric and chromospheric network bright points and the small-scale magnetic fields.

Acknowledgements. We thank Dr. J. Bruls for carefully reading the manuscript and for his critical and helpful comments. The Vacuum Tower Telescope is operated by the Kiepenheuer-Institut für Sonnenphysik, Freiburg, at the Spanish Observatorio del Teide on Tenerife of the Instituto de Astrofísica de Canarias.

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