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Letter to the Editor

Regular structures of the solar photosphere

(Persistence of the granular field and trenching in the brightness relief)

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Abstract. The simple procedure of time averaging, when applied to the photospheric brightness field, reveals quasi-regular structures of the photospheric and subphotospheric flows. We use an 8-h sub-set of the series of photospheric images obtained on 5 June 1993 with the Swedish Vacuum Solar Telescope, La Palma. First, the averaged images are far from completely smeared and contain a multitude of bright, granular-sized blotches even if the averaging period is as long as 8 h. This suggests that granules prefer to originate at certain sites, where they emerge repeatedly, and the granular field demonstrates a sort of persistence for many hours. Second, the resulting patterns display relatively regular structures, which can be revealed only if the averaging period is sufficiently long (the optimum seems to lie between 2 and 3 h). The averaged brightness relief is "trenched": it comprises systems of concentric rings and arcs as well as straight or slightly wavy lines and systems of parallel strips. The trenching patterns resemble the so-called target patterns observed in experiments on Rayleigh–Bénard convection. In addition, the brightness values at a local averaged-field maximum and at a nearby minimum exhibit a distinct tendency to vary in antiphase. Thus, a previously unknown type of self-organization is manifest in the solar atmosphere, and our findings support the suggestion that granules are associated with overheated blobs carried by the convective circulation.

Key words. solar photosphere – granulation – convection patterns

1. Introduction

In recent years, solar physicists succeeded in obtaining long, extremely informative series of high-quality images of the solar photosphere. The most significant achievement on this avenue was the sequence of images of a 118.7×87.9 Mm^2 area of the solar photosphere obtained by Brandt, Scharmer, and Simon (see Simon et al. 1994) on 5 June 1993 with the Swedish Vacuum Solar Telescope (La Palma, Canary Islands). This series still remains unsurpassed in terms of duration (11 h), continuity (a constant, 21-s frame cadence), and quality (rms contrast varying between 6 and 10.6%). Such observational material opens the door to a systematic and detailed exploration of the structures of photospheric and subphotospheric flows.

As a rule, the technique of local correlation tracking (LCT) is employed to study photospheric flow structures. This procedure uses granules as tracers "visualizing" plasma motion and yields the field of horizontal velocities (see November 1986). In fact, the local velocity vector obtained in a particular measurement reflects the movement of the *centre of gravity* of the brightness field within the small area chosen for this measurement and, as shown by Title et al. (1989), strongly depends on the area size. Similarly, the result should be sensitive to the spatial resolution of the images.

Using the LCT technique made it possible to reveal some features of spatial organization in granulation patterns, related to the transport of granules by mesogranular and supergranular flows (whose convective nature is commonly assumed). A cellular structure corresponding to a superposition of these two flow types was identified in the velocity field (Title et al. 1986). It was found that granules move away from the central parts of mesogranules and disappear at their peripheries; in turn, mesogranules are carried by supergranular flows (Muller et al. 1992; Shine et al. 2000).

As thermal convection takes place in a horizontal fluid layer heated from below, the horizontal temperature distribution at a given height reproduces, to a first approximation, the horizontal distribution of the vertical velocity component at the same height. Under solar conditions,

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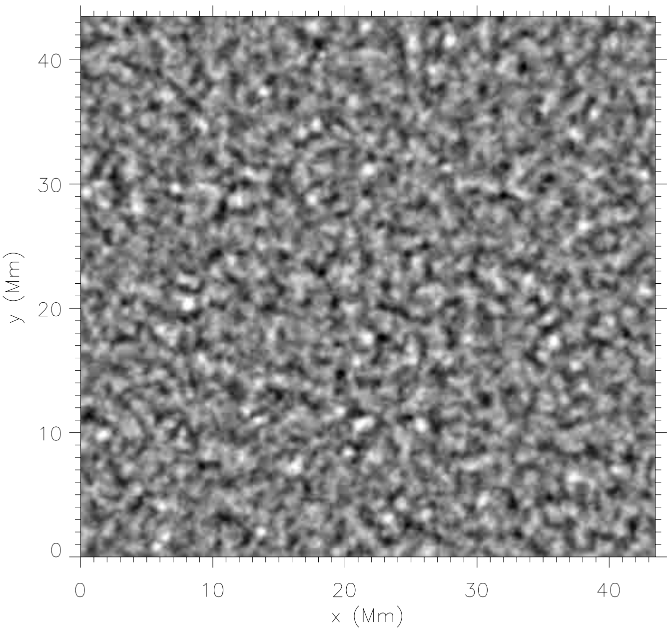

Fig. 1. Granulation pattern averaged over the entire 8-h timespan of the data sub-set (8:25:40–16:38:52 UT). The rms intensity contrast is 1.35%.

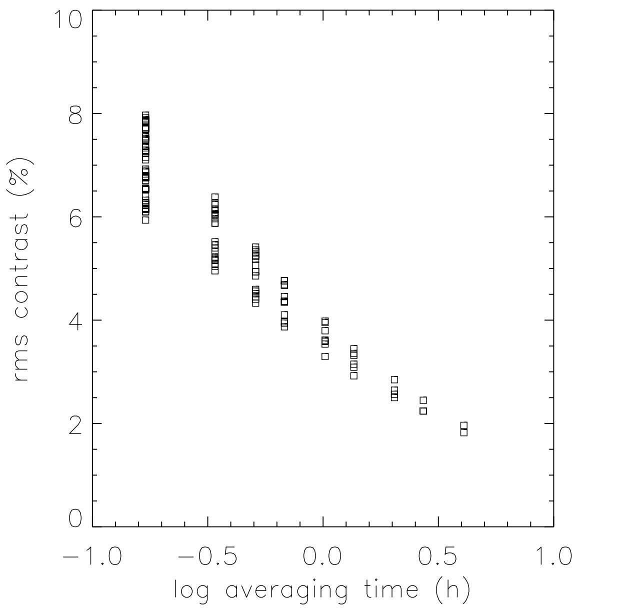

Fig. 2. The rms intensity contrast of the averaged images as a function of the averaging time.

convection permanently carries blobs of overheated material to the photospheric surface from lower layers, and these blobs are observed as granules – this notion is suggested by qualitative analyses of modern series of observations (see a discussion in Getling 2000) and confirmed by the findings presented below. Therefore, the temperature and the vertical-velocity distribution over the photospheric surface should be similar when averaged over time. Similarly, we can expect the time-averaged field of the vertical velocity component to be mainly represented by the time-averaged brightness field. The latter should be a more direct and more detailed imprint of the flow pattern than the field obtained by the LCT technique. Moreover, in contrast to LCT, the brightness-averaging procedure does not depend on externally specified parameters.

To study the structure of photospheric flows, we applied the averaging technique to an 8-h sub-set of the above-mentioned La Palma series of solar images. Here, we present some results obtained in this way.

2. Observations and data reduction

The observations lasted from 08:07 to 19:07 UT on 5 June 1993. The images of the Sun produced by the Vacuum Solar Telescope in the 10-nm-wide spectral band centred at a wavelength of 468 nm were recorded by a CCD camera at a rate of 3.7 Hz. Each frame contained 1310×970 pixels; the pixel size was $0.125''$, and the frame covered a 119×88 Mm^2 quiet-Sun area, not far from the disk centre. The resolution was typically no worse than about $0.5''$. A frame-selection system (Scharmer & Lofdahl 1991) determined the rms contrast of each image in real time and selected two images of highest contrast during any 15-s interval. After that, 6 s were spent to record these frames on magnetic tape, yielding a complete cycle time of 21.03 s. Subsequently, the better image of the pair recorded during the cycle was chosen for further analysis.

The primary data reduction included the alignment of contiguous images, LCT-based destretching, and subsonic Fourier filtering (Title et al. 1989), which eliminated fast time variations (the cutoff phase speed was 4 km s^{-1}). The Fourier transform technique was used to interpolate the images to equal time lags of 21.03 s. The entire series, which lasted about 11 h, contains almost 1900 frames. For a more detailed description of the data acquisition technique see Simon et al. (1994).

The results presented here were obtained by means of averaging the brightness fields of a sub-set of the series over varying time intervals. The sub-set covers a 43.5×43.5 Mm^2 area ($60'' \times 60''$, or 480×480 pixels) and an 8-h interval (1408 frames). To make the printed images in the paper clearer, we artificially enhanced their contrast.

3. Results

First of all, the averaged images are far from completely smeared, even if the averaging period is as long as 8 h, i.e. covers the entire sub-set (Fig. 1). On the contrary, the resulting picture is mottled and contains a multitude of bright granular-sized blotches. The rms contrast, smoothly decreasing with the increase of the averaging time (Fig. 2), is nevertheless as high as 1.35% for the 8-h average, i.e., only 4–8 times lower than the contrast of individual frames. The 8-h timespan exceeds the characteristic lifetime of a granule by one and a half orders of magnitude. Thus, the points of origin are not quite random for granules, and certain sites appear to be preferred.

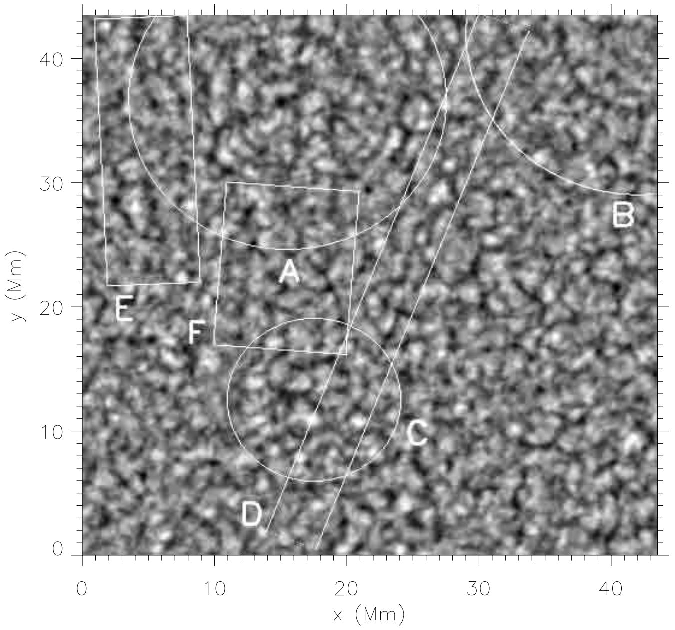

Fig. 3. Granulation pattern averaged over a 2-h timespan of the data sub-set (14:26:43–16:29:03 UT). The rms intensity contrast is 2.92%.

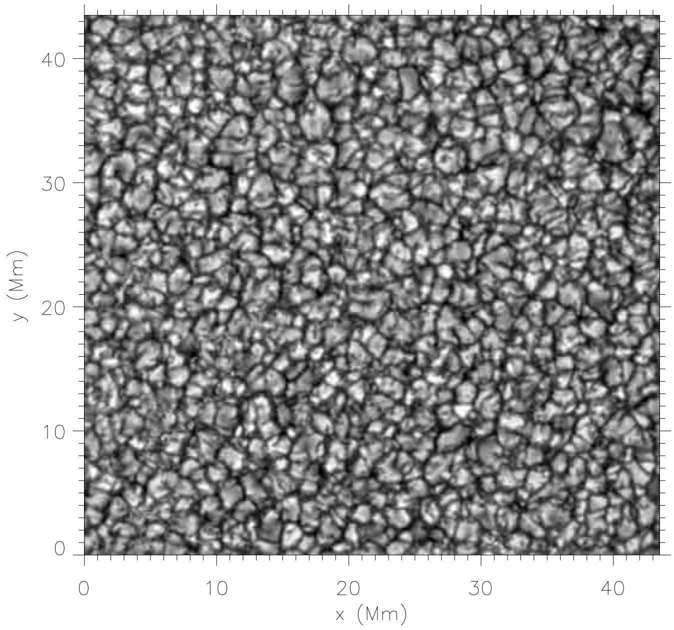

Fig. 4. Single granulation image obtained at 15:30:09 UT, near the middle of the 2-h timespan used to construct Fig. 3. The rms intensity contrast is 10.3%.

Earlier, Baudin et al. (1997) noted the mottled appearance of a 109-min-averaged image. They attributed this effect to the persistence of the granules themselves. In contrast, we see clear indications for the recurrent appearance of granules at the same sites. Specifically, the time variation of brightness at the points of local maxima of the averaged field (not presented here) exhibits sequences of well-defined peaks whose periods of repetition correspond in order of magnitude to the commonly assumed characteristic lifetime of granules (ca. 10 min). The relative amplitudes of the brightness variations crudely correspond to or even exceed the rms contrast of individual images.

Comparing the brightness-variation curves for a local maximum and a nearby minimum of the averaged brightness reveals the following remarkable feature. In many cases, the two curves are well correlated, and the brightnesses at the "dark" and the "bright" blotch vary mainly in antiphase. Even fine details in one curve may have their counterparts in the other.

Another important property of the averaged images is the presence of relatively regular structures. Moreover, they can be revealed only if the averaging interval is sufficiently long – crudely, if it exceeds 1–1.5 h. An example of a brightness distribution with well-defined structures of this sort is given in Fig. 3. The picture is completely dissimilar to a continuous network of mesogranules or supergranules. Instead, the averaged brightness relief is "trenched"; in other words, the image comprises relatively regular concentric rings and arcs (some of them are marked with surrounding circles A, B, and C in the figure), as well as straight and slightly wavy lines and systems of parallel strips (enclosed in boxes D, E, and F). Such structures are formed by families of parallel chains of bright and of dark blotches. We shall call them ridges and trenches, respectively.

Structures of this type are best distinguishable if the averaging interval lies between 2 and 3 h. As the length of this interval is further increased, the structures gradually become less pronounced, although traces of some features remain identifiable even in the case of the 8-h averaging. In particular, indications for the presence of the system of circular arcs marked as system B in Fig. 3 can also be found in Fig. 1. Generally, different features are most distinct at different averaging intervals. This suggests that the features differ in their lifetime, and intermittency is possible in their behaviour, i.e., periods of elevated and lowered activity of the processes forming these structures may alternate. For instance, a clear-cut trench that extends from the upper left corner of the frame toward its centre can be seen in Fig. 1. It blurs as the averaging interval is shortened.

Is is worth noting that Rieutord et al. (2000) observed intermittency in the divergence field of the (LCT-based) horizontal velocities on a mesogranular scale.

The above-described, long-lived structures are almost indistinguishable in instantaneous, highly variable granulation patterns. The dissimilarity between the averaged and instantaneous patterns can be noted if we compare Fig. 3 to Fig. 4 that displays a frame taken near the median time of the interval over which the brightness field shown in Fig. 3 is averaged.

4. Discussion and conclusion

Except Baudin et al. (1997), some other investigators previously noted signatures of the prolonged persistence

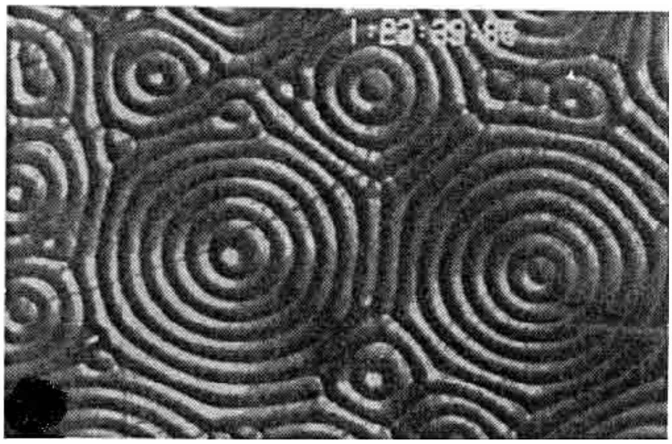

Fig. 5. A target pattern of curved convection rolls experimentally observed by Assenheimer & Steinberg (1994).

of granulation patterns. Roudier et al. (1997) detected long-lived singularities (dark features) in the network of intergranular lanes and termed them intergranular holes. They were continuously observed for more than 45 min, and their diameters varied from 0.24″ (180 km) to 0.45″ (330 km). Later, Hoekzema et al. (1998) and Hoekzema & Brandt (2000) also studied such features, which had been observable for 2.5 h in some cases.

Our results demonstrate that many-hour persistence is an inherent property of granulation. The recurrent emergence of granules at the same sites (which is quite evident from the brightness-variation curves not presented here but briefly described above) supports the surmise that granules should be identified with overheated blobs carried by the convective circulation (Getling 2000). If the actual lifetime of such a blob is much longer than its time of passage from the upwelling to the downwelling zone of the convection cell (the apparent lifetime of the granule), then, in general, the blob may emerge on the surface repeatedly, producing a bright spot in averaged images. In this case, the lifetime of the cell proves to substantially exceed the turnover time of the circulating material.

The appearance of the averaged images suggests that the subphotospheric convection cells of the smallest (granular) scale resemble convection rolls (the best studied form of convection in horizontal fluid layers heated from below; see, e.g., Getling 1998) of either circular or linear shape. On the whole, the picture resembles the so-called target patterns of curved convection rolls, which were observed by Assenheimer & Steinberg (1994) in their thermal-convection experiments (Fig. 5). The outer sizes of the systems of concentric rings and arcs lie in the mesogranular range (5–10 Mm). Alternatively, it is not inconceivable that precisely such systems are substantive entities in the flow, while ridges and trenches form their fine structure.

Numerous studies have tackled the problem of pattern formation in convective phenomena (for a review, see Getling 1998); however, the regularities of transitions between quasi-two-dimensional and target-type (or spiral) roll patterns still remain poorly understood. It should only be noted that the vertical distribution of the material properties of the fluid, related to their dependence on the physical conditions, is an important factor affecting the selection of one pattern or another.

Our findings reveal a previously unknown type of self-organization in the solar atmosphere. Parallel studies of the patterns arising under the complex solar conditions and under “refined” conditions in laboratory or numerical experiments could elucidate many important properties of the Sun as a pattern-forming system and, at a later time, give a clue to the diagnosis of the state of subphotospheric layers based on observations of photospheric structures.

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