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Regular Photospheric Patterns (Trenching in the Brightness Relief) and Persistence of the Granular Field

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Abstract. The simple procedure of time averaging is applied to the photospheric images of the La Palma series of 1993. The resulting images are far from completely smeared, even if the averaging period is as long as eight hours, and comprise a multitude of bright granular-sized blotches, where granules emerge repeatedly. Thus, granules prefer to originate at certain sites, and the granular field demonstrates a sort of persistence for many hours. In many cases, the correlation between the brightness variations at a local averaged-field maximum and at a nearby minimum supports the surmise that granules are overheated blobs carried by the convective circulation. If the averaging period is about 1.5 h or longer, 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. A similar pattern can be seen in a 2-h-averaged map of the horizontal-flow divergence obtained using local correlation tracking. The trenching pattern resembles so-called target patterns observed in experiments on thermal convection in a horizontal fluid layer heated from below. Thus, a previously unknown type of self-organization is manifest in the solar atmosphere.

1. Introduction

A consistent notion of the structure of solar convection on various scales still remains to be formed. At least some of the characteristic scales should be manifest at the photospheric level, but the corresponding patterns of fluid motion can be comprehensively investigated only if the available information on the dynamics of photospheric and subphotospheric layers covers the spatial and temporal scale ranges under study.

In this context, the most significant achievement of observational solar physics 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%).

As a rule, the technique of local correlation tracking (LCT) is currently employed to study photospheric flow structures (see November 1986). This procedure uses granules as tracers "visualizing" plasma motion. It should, however, be noted that the local velocity vector obtained in an individual LCT measurement strongly depends on the size of the area chosen for this measurement (Title et al. 1989).

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. Qualitative analyses of modern series of observations of the solar photosphere suggest (Getling 2000) that solar convection permanently carries blobs of overheated material to the photospheric surface from deeper layers, and these blobs are observed as granules. The findings presented below confirm this notion. Therefore, the temperature and the vertical-velocity distribution over the photospheric surface should be similar when averaged over time. Accordingly, we can expect the time-averaged field of the vertical velocity component to be mainly represented by the time-averaged brightness field. Thus, the latter should be a more direct and more detailed imprint of the underlying flow pattern than the field obtained using the LCT technique. Moreover, in contrast to LCT, the brightness-averaging procedure does not depend on externally prescribed 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 centered 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 center. 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 out of 55 ones obtained 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 (i) the alignment of contiguous images—they were shifted relative to each other to obtain best correlation between the intensity patterns, (ii) destretching—the compensation of the seeing-introduced distortion by applying a LCT technique and an interpolation scheme, and (iii) subsonic Fourier filtering (Title et al. 1989), which eliminated fast time variations (the cutoff phase speed was 4 km/s). The Fourier transform technique was used to interpolate the images to equal time lags of 21.03 s. The entire se-

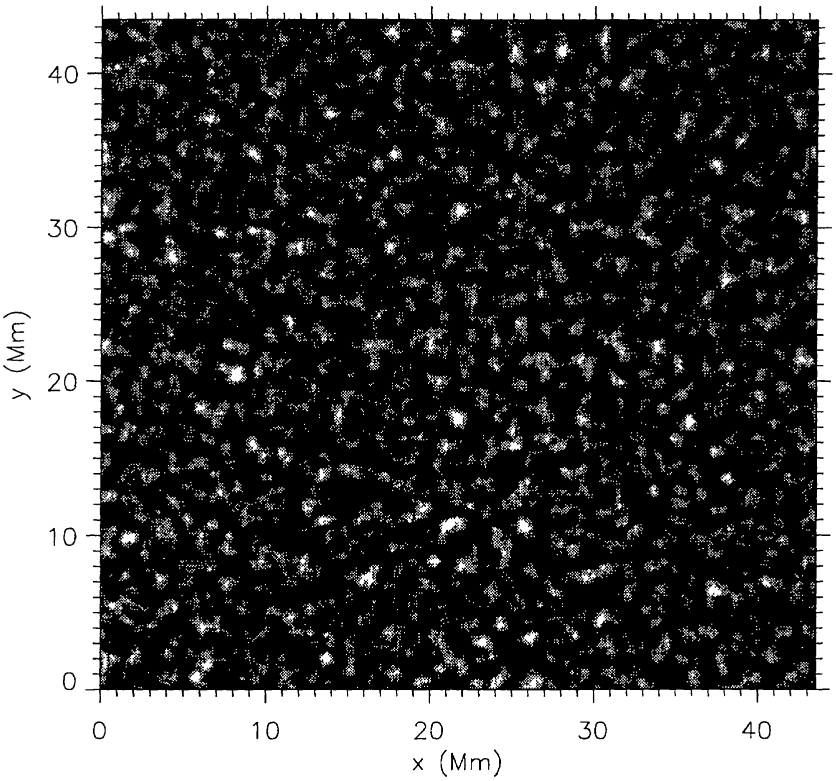

Figure 1. Granulation pattern averaged over the entire 8-h time span of the data sub-set (8:25:40-16:38:52 UT). The rms intensity contrast is 1.35%

ries, 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″×60″, or 480×480 pixels) and an 8-h interval (8:25:40–16:38:52 UT; 1408 frames). As a rule, the averaging procedure was carried out over intervals multiple of 30 min 51 s, which comprises 88 frame cadences. To make the printed images in this paper clearer, we artificially enhanced their contrast by applying the bytescaling procedure, which sets the intensity minimum to zero and the maximum to 255.

3. Results

First of all, it is remarkable that the averaged images are far from completely smeared, even if the averaging period is as long as 8 h, i.e., if it 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 decrease in the average rms intensity contrast with the increase of the averaging time τ is markedly slower than $\tau^{-1/2}$ (Fig. 2), and for long averaging intervals the contrast exceeds the values that could be expected in the case of purely chaotic emergence of granules. For the 8-h average, the contrast is 1.35%, i.e., only 4–8 times lower than the

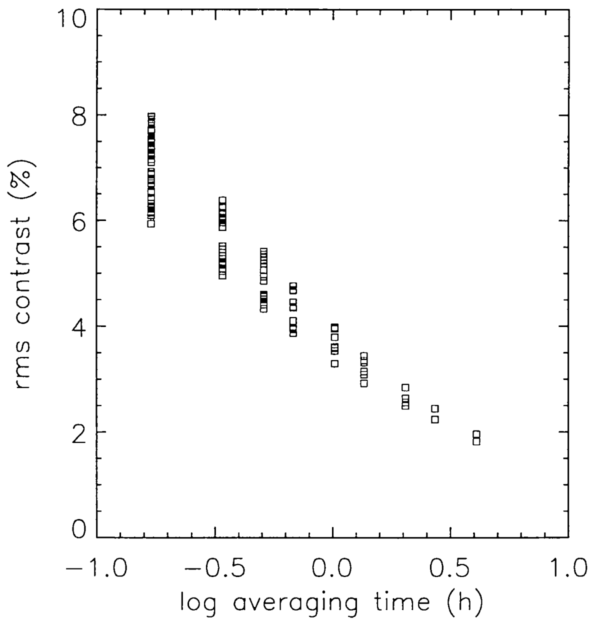

Figure 2. The rms intensity contrast of the averaged images as a function of the averaging time.

contrast of individual frames. The 8-h time span exceeds the characteristic lifetime of a granule by one and a half orders of magnitude. Thus, granules prefer certain sites to originate at, rather than emerge quite randomly.

To comprehend how this mottled pattern is formed, we analyzed the time variation of brightness at some selected pairs of points. In each pair, one point was situated approximately at a local maximum of the averaged brightness field and the other at a *nearby* minimum. For technical reasons, this has been done only for the 2-h time span that lasted from 14:26:43 to 16:29:03 UT. The image averaged over this interval, which has an rms contrast of about 3% (2–3.5 times lower than the contrast of individual frames), is presented in Fig. 3.

From the brightness-variation curves (not presented here) we see clear evidence for the recurrent appearance of granules at the same sites: the time variation of brightness 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). This is especially pronounced at the points of local maxima of the averaged field.

A preliminary analysis of the brightness correlation between the "bright" and "dark" points of the selected pairs revealed some characteristic types of correlations. Among them, correlations nearly periodic in time lag are most interesting, since they support the notion that granules are carried by convective circulation and may repeatedly emerge on the solar surface. More detailed studies of the regularities in the correlation of the brightness variations are now underway.

Another important property of the averaged images is the presence of relatively regular structures, which cannot be distinguished in individual frames.

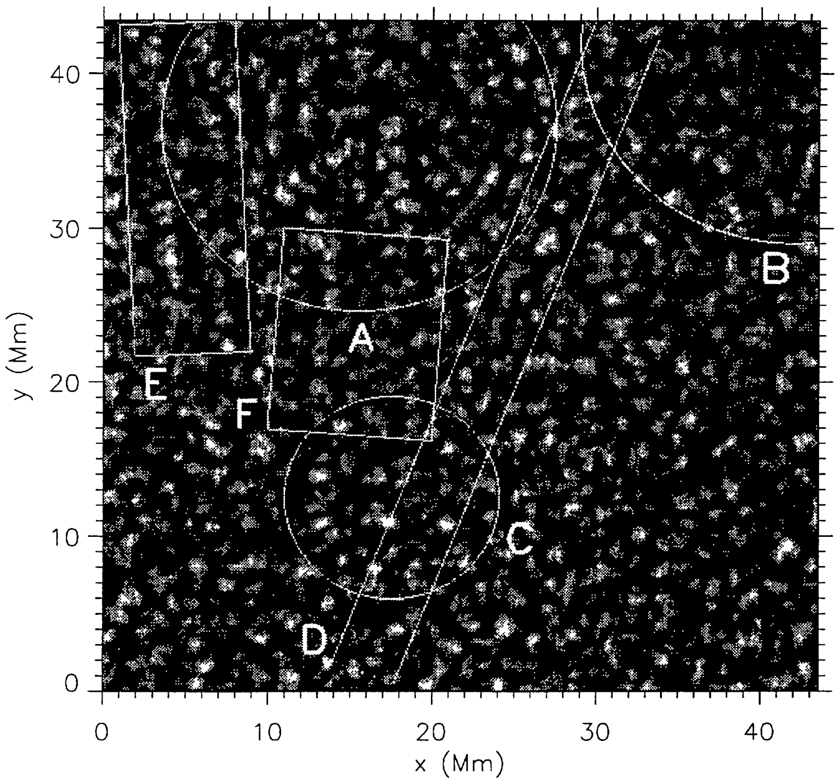

Figure 3. Granulation pattern averaged over a 2-h time span of the data sub-set (14:26:43–16:29:03 UT). The rms intensity contrast is 2.92%.

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 will 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 indicates that the features differ in their lifetime, and intermittency is possible in their behavior, 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 center can be seen in Fig. 1. It blurs as the averaging interval is shortened.

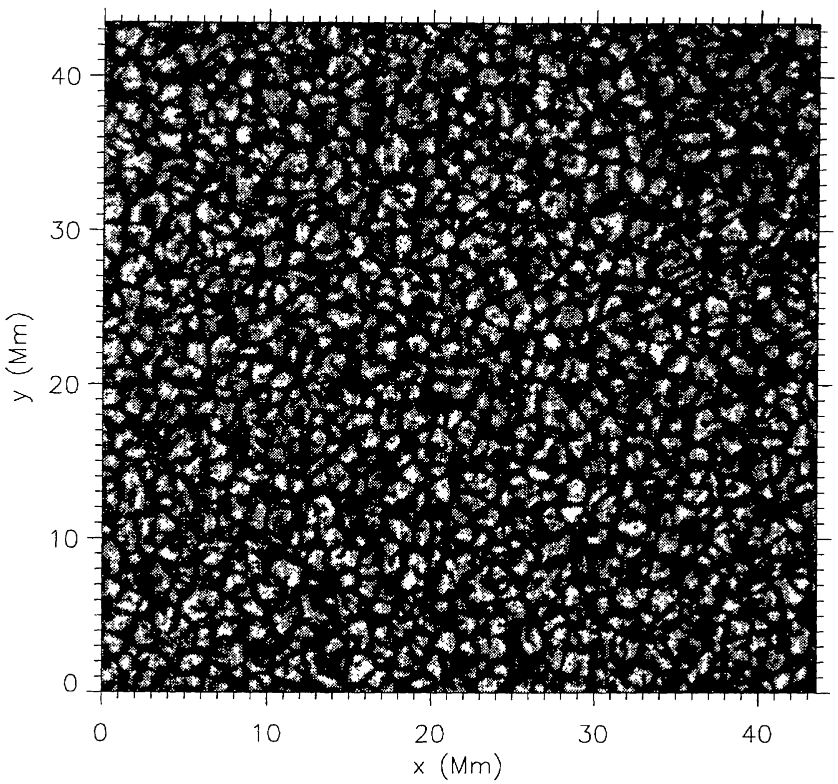

Figure 4. Single granulation image obtained at 15:30:09 UT, near the middle of the 2-h time span used to construct Fig. 3. The rms intensity contrast is 10.3%.

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.

On the other hand, agreement was found between these structures and the structures revealed in the field of the horizontal-velocity divergence inferred from LCT maps and averaged over the same interval (this field has not yet been carefully analyzed).

4. Discussion and Conclusion

Signatures of the prolonged persistence of granulation patterns have already been noted by some investigators. Baudin et al. (1997) reported the mottled appearance of a 109-min-averaged image. 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.

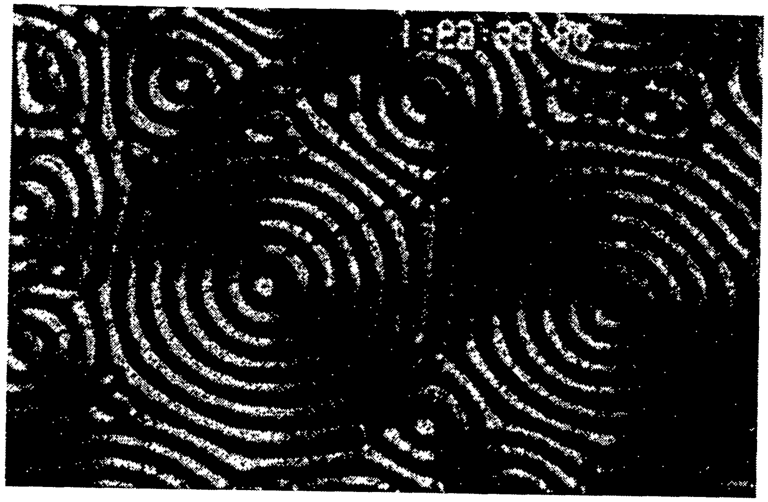

Figure 5. A target pattern of curved convection rolls experimentally observed by Assenheimer & Steinberg (1994)

Our results demonstrate that many-hour persistence is an inherent property of granulation. The recurrent emergence of granules at the same sites supports the surmise (Getling 2000) that granules should be identified with overheated blobs carried by the convective circulation. In particular, such overheated blobs may result from some types of instabilities in this circulation. If the actual lifetime of such a blob is much longer than its time of passage from the upwelling to the downwelling zone in 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.

In the case of recurrent emergence of granules, the "bright" points in the selected pairs should correspond to upwellings in the flow of the solar plasma and the "dark" points to downwellings. Under idealized conditions of the strictly periodic emergence, the correlation between the "bright" and the "dark" point would be a periodic function of the time lag. In many cases, we see a crudely periodic behavior of such correlation functions.

In addition, from LCT-based maps of the horizontal-velocity field, we have prepared a 2-h-averaged divergence map in which one can distinguish the same structures as in the image averaged over that very 2-h interval (Fig. 3).

Let us assume that the long-lived structures are really an imprint of the photospheric and subphotospheric flow pattern. Then the appearance of the averaged images suggests that the subphotospheric convection cells of the smallest 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 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). If the ridges and trenches themselves, rather than their larger scale aggregations, correspond to some individual flow forms (like convection rolls), then the scale of these structures is intermediate between the granular and mesogranular scales. Alternatively, it is not inconceivable that precisely such larger scale systems represent 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 (see Getling 1998 for a review); 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. Even very fine details of the stratification can be of crucial importance. In some cases, however, transitions occur without any marked changes in the stratification.

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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