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Intergranular plumes and formation of network bright points

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Abstract. We discuss the temporal evolution of the photospheric intergranular lanes using a 1 hour time sequence of white-light images of solar granulation. The time series was obtained with the 50 cm refractor at the turret dome of the Pic du Midi Observatory. Analysis reveals the existence of singularities in the intergranular lanes that we call “intergranular holes”. Intergranular holes, which have diameters between 0.24 arcsec and 0.45 arcsec, are continuously visible for more than 45 minutes. The holes appear to be systematically distributed at the periphery of mesogranular and supergranular cells. Our study reveals the formation of bright points (BPs) in 4 out of 14 cases studied very close to the intergranular holes, suggesting that intergranular holes may be the locations where magnetic flux tubes are formed.

Key words: Sun: granulation – photosphere – methods: data analysis – convection

1. Introduction

Magnetic structures in the quiet sun appear as discreet elements called ”flux tubes” which form the classical Photospheric Network. The dynamics and evolution of these flux tubes are in particular related to convection properties in the outer layer of the sun. More precisely the mechanism that controls the processes and physics of magnetic flux tubes is intimately connected to the properties of solar granulation and mesogranulation. The relation between magnetic fields and intergranular lanes has been elucidated in recent studies (Dunn and Zirker 1973,Muller 1983). Title et al. (1987) show a good correlation between granular downflow and concentrated magnetic field which can be identified as Bright points (BPs) in whitelight and CH (G band) observations (Keller 1992, Berger et al 1995). These Bright points are more likely to be in the intergranular lanes in the converging flow areas outside mesogranular cells (Muller et al. 1994). Such BPs are then swept to the supergranule boundaries (Simon et al. 1991) and apparently form the photospheric network.

One of the more interesting results of general relevance to the issue of magnetic-flux-tube generation with convective downflows is the novel photospheric vortex feature discovered by Brandt et al. (1988) indicating a “bath tub” effect, that is large vorticity, where the plasma converges into a downdraft. That particular vortex persisted for 79 min. in their time sequence, and could be a location where the footpoints of magnetic flux tubes are generated and twisted. Nevertheless, this observation stands alone as no other similar cases had been reported prior to our present analysis.

Theory and numerical modelling predict that magnetic fields tend to coalesce at downward convective flows (Solanki 1989, Spruit et al. 1992) which is in good agreement with observations which have been made. From another point of view, recent theoretical works have brought to some new reasons for studying the properties of the intergranular where downdraft are located motions (Hulburt et al. 1984, Chan and Sofia 1986, Stein and Nordlund 1989, Cattaneo et al. 1991, Rast and Toomre 1993a, 1993b, Rast et al. 1993c, Rieutord and Zahn 1995). These authors reported special features of convective downdraft motions at the solar surface in the overall energy transport and dynamics on the basis of numerical simulations. Their works generally indicate the existence of strong long-lasting downdrafts. Cool plumes form at the solar surface and penetrate downward into the convection zone. Other phenomena of strong downflows at the centers of exploding granules have been predicted by Rast (1995) and Steffen et al (1989), consistent with their observed topology. Rast (1995) also suggested that mesogranulation may be determined by strong long-lasting downflow events.

Thus the intergranular flow properties appear today to be of crucial importance for understanding the flux tube generation, oscillations (Espagnet et al 1996) and more generally the dynamics of different convective scales observed on the sun surface. The principal dynamic properties of intergranular areas have been described by different authors (Namba et al. 1983, Kavetsky and O’Mara 1984, Wiehr and Kneer 1988, Guenter and Mattig 1990, Hanslmeier et al. 1990, 1991a, 1991b, Nesis

Send offprint requests to: Th. Roudier et al. 1992), but only a few papers have been published on the temporal morphology properties of the intergranular lane(eg. Amalśkaya, 1990). This is partially because of the difficulties in obtaining a very high resolution long time sequence which covers a large field of view and also in defining numerical methods that separate the intergranular areas from the bright granules. The main result, concerning intergranular morphological properties, shown by Amalśkaya (1990) is the existence of intergranular "starlike" homocentric structures (size=3.3 arcsec mean lifetime=3.1 mn.) containing a few beams and a dark knot (100-200 km) in their center.

In the present paper, we focussed our analysis on the temporal and spatial properties of the granulation dark lane. This was achieved by using a new image filtering method, the wavelet transform described in Sect. 3. The wavelet transform appears to be reproducible from image to image, allowing for our analysis of the temporal properties of the intergranular lanes and the BP location in Sects. 4 and 5.

2. Observations and reduction

The present work is based upon an observation of solar granulation obtained on September 20, 1988 at the Pic du Midi Observatory which has already been used several times to investigate the properties of solar mesogranulation (Frank et al. 1989, Muller et al. 1992), and of the bright points (BPs) (Muller and Roudier 1992, Muller et al. 1994, Roudier et al. 1994). To summarize, it consists of a 3-hour time series of white-light (5750 Å passband = 60 Å) photographs taken every 20 seconds over a field of view of 100×70 arcsec. The frame quality approaches the diffraction limit of the telescope which is of 0.23 arcsec at this wavelength.

The successive frames have been digitized, aligned, destretched and undergone space-time "subsonic" filtering to eliminate waves with phase velocity of more 4 km/s through the processing developed at the National Solar Observatory in Sunspot and LPARL (for references see Roudier et al. 1994). Due to the limited storage capacity of our computer used for the data processing, we have focused our analysis on the best subset of 1 hour out of our 3-hour sequence. This subset of 173 frames (57 minutes duration) in a subfield of 31×33 arcsec (with pixel size and step of 0.08 arcsec) was used for the present investigation (example in Fig. 1).

3. Data reduction

One of the major difficulties in studying the intergranular lane comes from the criterion used to locate it. Typically, lane finding algorithms are based on the identification of local minima (Topka and Title 1992) or on Fourier filtering and segmentation methods (Roudier et al. 1986). The first method is much more accurate being less sensitive to image noise and granulation fragmentation, but requires that missing parts of the lane be filled in to form a continuous intergranular lane. In this work we show the viability of wavelet filtering for studying the intergranular lanes, a technique recently demonstrated in different studies by Coupinot et al. (1992).

Wavelet filtering consists of convolving an image with a wavelet kernel of adjustable scale size. The wavelet transform can be used to decompose an image into filtered images using masks with varying sizes. The procedure gives a decomposition of the image into a set of maps which exhibit structures at different scales (Coupinot et al. 1992). For intergranular lane features, we selected a Gaussian analyzing function because it nicely fit the mean intergranular profile. The wavelet transform is defined as:

$$T_{\Delta}(\mathbf{x}) = \int_{-\infty}^{+\infty} F(\xi) G\left(\frac{\xi - \mathbf{x}}{\Delta}\right) d\xi \qquad (1)$$

The image $F(\mathbf{x})$ is convolved in the 2D image domain $\mathbf{x}$ by a filter with a bandwidth defined by the spatial scale Δ. This parameter is called the "spatial scale of the wavelet". The selected $G(\mathbf{x})$ analyzing wavelet, the so-called"Mexican hat", is defined as:

$$G(\mathbf{x}) = \frac{1}{\pi\Delta^2}\left(2 - \left(\frac{|\mathbf{x}|^2}{\Delta^2}\right)\right) \exp\left(-\frac{|\mathbf{x}|^2}{2\Delta^2}\right) \qquad (2)$$

This choice of wavelet kernel is optimum in its signal/noise properties, and gives a reproductible signal even with changing seeing conditions.

One of the convenient characteristics of this kernel function is that it acts as a spatial passband filter. Thus it is possible to separate the intergranular lanes from granulation and automatically eliminate granular intensity changes and dynamics from the study (Coupinot 1994). In order to filter only the high frequency domain where the intergranular scale is present, we have selected the scale parameter $\Delta = 2$ pixels = 0.16 arcsecs.

After the filtering, the scaled map is binarized by applying a threshold discriminator to better indicate the intergranular fine structure. The threshold was selected in order to get the best visual fit between the original frame and the selected binarized intergranular structure. This processing was applied to the entire 1 hr time series with the same threshold value. A meticoulous visual check was then performed to validate the selected threshold. With our wavelet filtering technique, we were able to eliminate features that confuse the temporal analysis of the intergranular-lane features by optimizing the choice of the spatial window size. Wavelet processing is applied in the spatial domain without a temporal component. Thus, it does not introduce temporal coherence. Fig. 1 (a and b) shows one example of the good agreement between the observation and the binarized map obtained from wavelet filtering. The intergranular lanes appear clearly. This processing was applied to the entire 1 hr time series.

Different processing steps have been used in our data steps reduction to get the binarized map of the intergranular lane. The influence of these processes and some natural effects (seeing, limited diffraction,etc...) have to be taken into account to evaluate the validity of the final results. The optimal digitization of our data at the Shannon step enable to to study the signal in the discret domain without ambiguity. In this way, the limited resolution of the telescope was taken into account. The fluctuations of the resolution due to the seeing change were reduced by using destrecht technique. Such processing removed

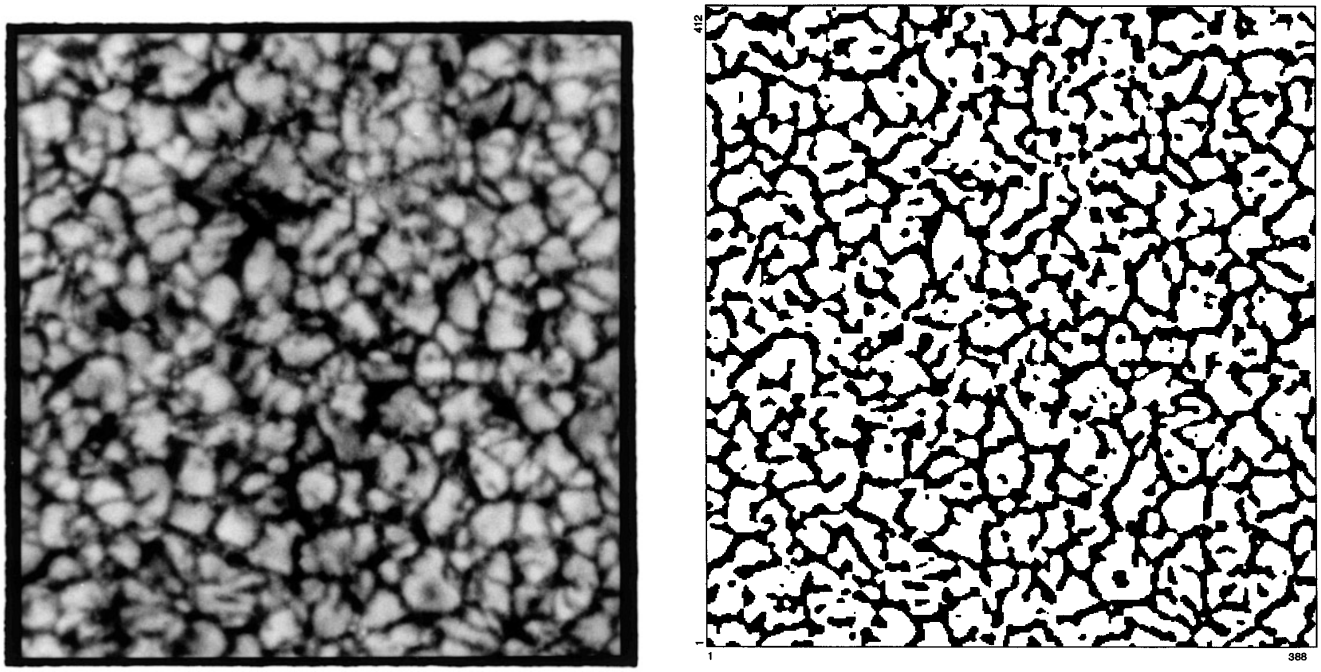

Fig. 1. a High resolution picture of solar granulation, in a 31 × 33 arcsec field of view, and **b** the binarized map of the intergranular lanes of the same field of view. The connected intergranular lanes appear to be clearly well detected.

all evolutionary phenomena, which are largely dominated by small scale high frequency random motions from the observation. The seeing distortions were strongly reduced by destretching the image frame by frame, using a grid of 3.4 arcsec x 3.4 arcsec sub-images, which proved to be the most suitable. This processing is designed to remove only high temporal random frequency without significant effects on the long temporal correlation of the data. The P-mode oscillations were filtered using a 3-D Fourier analysis (2 spatial and 1 temporal dimensions) in the k-omega space. For more accuracy, the whole data set was used for Fourier analysis. The artefacts introduced by such filtering have been described by Espagnet et al (1996). It has been shown that the residual fluctuation produced by an artificial "dark hole" (like a dark and large lane) in the raw pattern is only 0.13% with a quick dampdown.

So, our temporal analysis of the interganular lanes does not appear to have been quantitatively affected by our processing chain and is quite reproductible.

4. Temporal behavior of the intergranular lane

Different methods can be applied to detect intergranular singularities. One consists, as done by Amalśkaya (1990) in following, whatever their spatial motions, the intergranular persistence and shape. The second one involves trying to detect the possible persistence of an intergranular lane at a fixed spatial place as was suggested by the existence of a vortex which lasted during 79 min. at quite the same location (Brandt et al., 1988). In the present study the detection of intergranular singularities at one fixed location has been privilegied, in order to detect a feature such as the one described by Brandt et al., (1988). Obvioulsy, all the moving interganule singularities which could exist, would not be detected by our method. Detection of the possible exis-

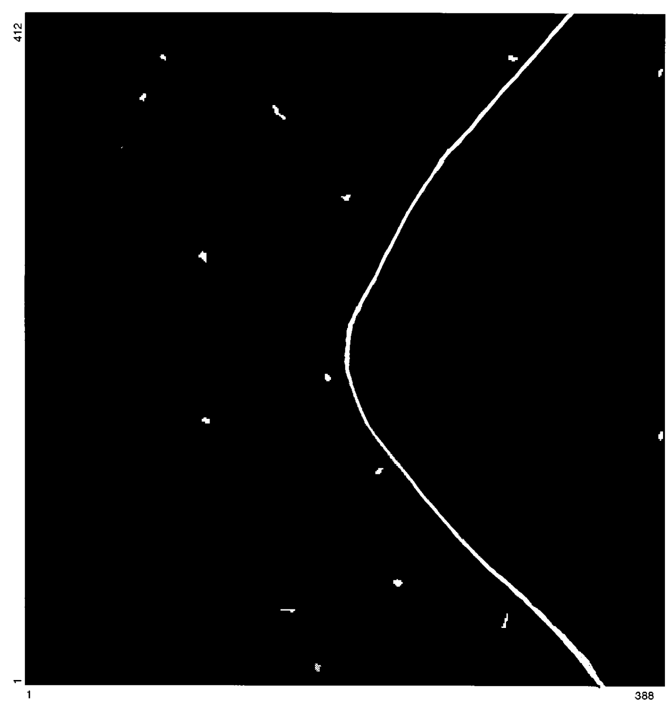

Fig. 2. Location of the intergranular singularities or holes that were continuously visible for at least 48 min. The white continuous line is drawn at the location of the supergranular boundary (see Muller et al 1992).

tence of singularities in the intergranular regions has been performed by using the sum of binarized maps of the granulation pattern obtained from wavelet filtering. Such processing reveals some intergranular singularities (Fig. 2.) where the equivalent duration, resulting from that sum, is greater than 45 minutes (3/4 of our analyzed time sequence). These intergranular singularities (white dots in Fig. 2) indicate the locations of relatively enhanced small features that exhibit a long *accumulated* total duration but not necessarily a continuous temporal persistence. However separate temporal analysis of these intergranular singularities shows that they are all continuously visible for more than 45 minutes. During their lifetimes, 3/4 of their areas are filled because of overlapping by adjacent granules that intrude on the edge of the structures. This process introduces some temporal discontinuities at the boundaries of the singularities. Their mean diameter is 0.35 arcsec (250 km), just above the limit of our spatial resolution. We found some examples that were as large as 0.45 arcsec (330 km).

The histogram of the continuous segments of intergranular on the time axis is shown in Fig. 3. Most of the distribution is below 400 seconds and peaks around 90 seconds. That value is just below of the one found by Amalśkaya (1990) of 186 seconds. It should be noted that few values greater than 40 minutes are present in the histogram because only 14 intergranular holes with a mean size of 15 pixels were in our field of view (388 x 412 pixels). The 1000 x and y positions randomly sampled only allowed few possibilities of obtaining a pixel with a duration of 45 minutes.

The persistence of such intergranular hole singularities is at least 7 times the duration of the previous limit (400 seconds) and 4 times the mean turnover time of granules. A rough estimation of the probability, at the Shannon step, of observing the persistence of dark structures by chance is quite small (see Appendix A). We believe that they are real distinct solar features and we call them "intergranular holes" which are spatially stable for at least 45 minutes, like the feature described by Brandt et al 1988 It is evident that the intergranular holes are preferentially located near the mesogranular converging flows and never inside the mesogranular source areas, as shown by the flow divergence map in Fig. 4. A few of them are located at the maxima of the converging flows. The intergranular holes therefore appear more likely to occur in the stronger longer-lived downflows. We also note that intergranular holes appear more likely to be located close to the supergranular chromospheric-network boundary drawn in Fig. 2.

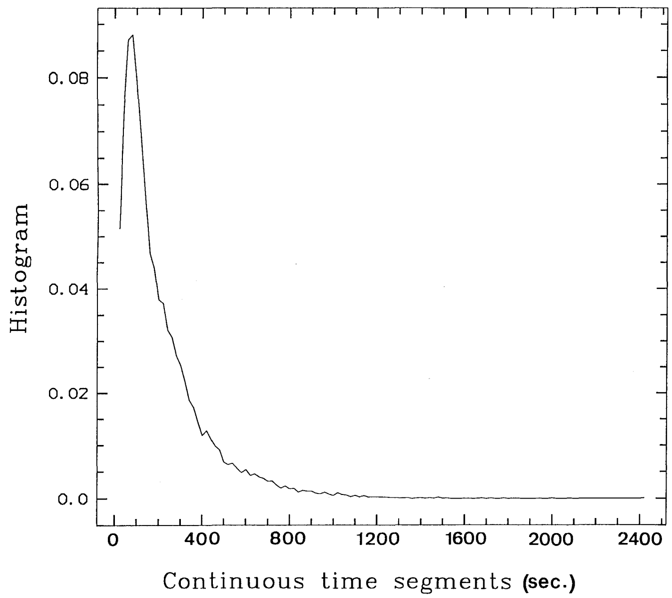

Fig. 3. Histogram of continuous segments of intergranular structures on thetime axis. This distribution has been obtained from 1000 x and y positions randomly sampled in the 3D binarized processed images.

5. Bright-point formation in intergranular holes

It is well established that intergranular dark lanes are associated with cool descending plasma. So intergranular holes can be considered as a continuous downflow location where the presence of magnetic structure can be suspected. In addition, there is evidence too for the strong downflow in the immediate surroundings of magnetic features from the measured Stokes V asymmetry (Solanki 1989, Spruit et al. 1992). We have tried to determine whether the intergranular singularities that we observed, can be specifically related to the observed locations for the appearance of BPs during the time series. A detailed inspection of the intergranular singularities present in our field of view, indicates the formation of BPs very close to intergranular holes in 4 out of the 14 intergranular holes studied; a total of 41 BPs have been identified in the field of view. The time series of intensity and vorticity shown in Fig. 5 gives the best example, where a BP is formed in an intergranular region and near an intergranular hole by the compression effect of adjacent moving granules (see Muller and Roudier 1992). Five minutes before the beginning of the compression and formation of the BP, a vorticity of 0.0045 sec^{-1} and lasting for more than 6 min 30 sec was found at that location. This short lived vortex point had a remarkably large vorticity, slightly greater than the vorticity for the flow reported by Brandt et al. (1988), which was 0.0014 sec^{-1}. This vorticity is $1/20$ of that required for vortex motions in the photosphere to be significant for coronal heating (Zirker 1993). From this example, we have the impression that there are two BP formation phases: vorticity appears to be followed by a compression of the intergranular space where the BP emerges. We believe that at these vortex structures there is probably a latent (or turbulent) magnetic field. Unfortunately, the small relative number of intergranular holes in our field of view, does not permit us to make more precise conclusions about the BP/intergranular-hole connection. We need observations made with a larger field of view and for a longer time such as the 11 hour granulation observation recently obtained by Simon et al. (1994) with simultaneous magnetic field measurements.

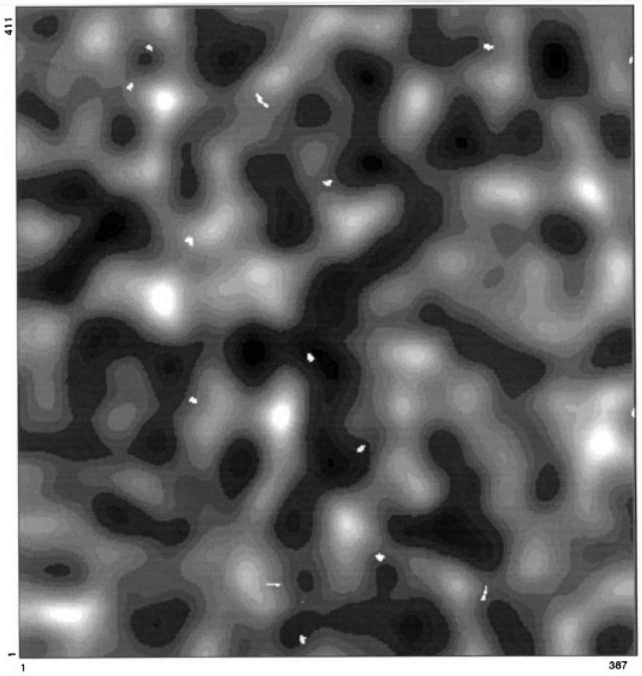

Fig. 4. Relative location of the intergranular singularities or holes with respect to the mesogranular diverging flow computed with a spatial window of 1.2 arcsec and a temporal window of 1 hour. The singularities appear to be preferentially located at the edge of the mesogranules.

6. Discussion and conclusion

Our analysis of the solar intergranular lanes has revealed a new morphological feature in the solar atmosphere, the "intergranular holes". Their reproducibility in successive processed images in a time series based upon high quality observations and our elaborate processing (which includes image alignment, destretching, subsonic filtering, and wavelet filtering) indicates reliable detection. Intergranule holes have diameters between 0.25 and 0.45 arcsec, and are continuously visible for more than 45 minutes. Their persistence does not seem to be based on chance (see Appendix A).

They are located preferentially at the periphery of mesogranular cells, and appear to be near the supergranular chromospheric-network boundary. A meticulous inspection of our data set also reveals that in 28% of the intergranular holes, there is a close Bright Point formation, suggesting a concentrated magnetic field presence. Two examples of short-lived anomalous vortex flows are found at these locations suggesting a relationship with vortex events. BPs seem more likely to form at some of the intergranular-hole locations, and this indicates associated enhanced vorticity events consistent with the major role played by downdraft motions in the dissipation and generation of magnetic fields. The examples shown here, indicate two phases in the BP formation process: a period of enhanced vorticity followed by a compression of the intergranular space.

Our observations of intergranular holes now suggests that an associated magnetic field (via BPs) may also be present in many of the strong long-lasting downdrafts or "plumes". Based upon the number in our small sample area, by extrapolation we estimated the number of intergranular holes over the whole solar surface to be around 100000. While the intergranular holes appear to indicate exceptional downflows preferentially located at mesogranular downflows, their total number still exceeds, by a factor of about 100 the number of principal downflow plumes that extend through the entire solar convection zone, as estimated by Rieutord and Zahn (1995). The intergranular holes may indicate the tops of the most extensive and deeply connected downflow plumes. This is probably why interganule holes seem to be present at the same location for at least 45 minutes. Convective plumes are probably responsible too for the dissipation of magnetic fields by helicity effects, and are very important in the generation of magnetic flux tubes by photospheric siphon flows according to mechanism recently determined by Degenhardt et al. (1993). The role of magnetic fields in the convective process may also not be entirely passive, as they may locally modify the convective energy transport. The combined dynamic and magnetic effects could provide the energy required for coronal heating although according to our limited estimates the available energy falls short of that requirement (Zirker 1993).

The temporal study of the filigree and magnetic field done by Yi and Engvold (1993), reveals that magnetic elements are advected in the local flows toward downdrafts at the supergranulation cell boundaries. They show a decrease of the flux density and of the intensity as the structures approach the downdraft. We may speculate that some of these preferential downdrafts could be related to the intergranular holes described in this paper. The intergranular holes are probably related to, or may be the same feature as the dark intergranular "pores" or "holes"identified by Title et al. (1987).

While an associated magnetic relation is suggested, the physics behind to the appearance of dark structures has not yet been understood. It is also possible that intergranular holes arise due to aliasing by the telescope/seeing point spread function on unresolved magnetic elements, which might exhibit special functional forms (Title 1995).

It is now of fundamental importance to get a longer time series with simultaneous magnetic-field measurements in order to quantify more precisely the magnetodynamical properties of intergranular holes. This will be possible in the near future at the Turret Dome (Pic du Midi with the monochromatic birefringent filter), or with the new Liquid Crystal Polarimeter at the National Solar Observatory Vacuum Tower Telescope (November and Wilkins 1995), and later with the new polarization-free telescope, THEMIS, which is scheduled to begin operation in 1996 at Tenerife. Infrared observations would also be very useful to understand the depth properties of such features below the photosphere.

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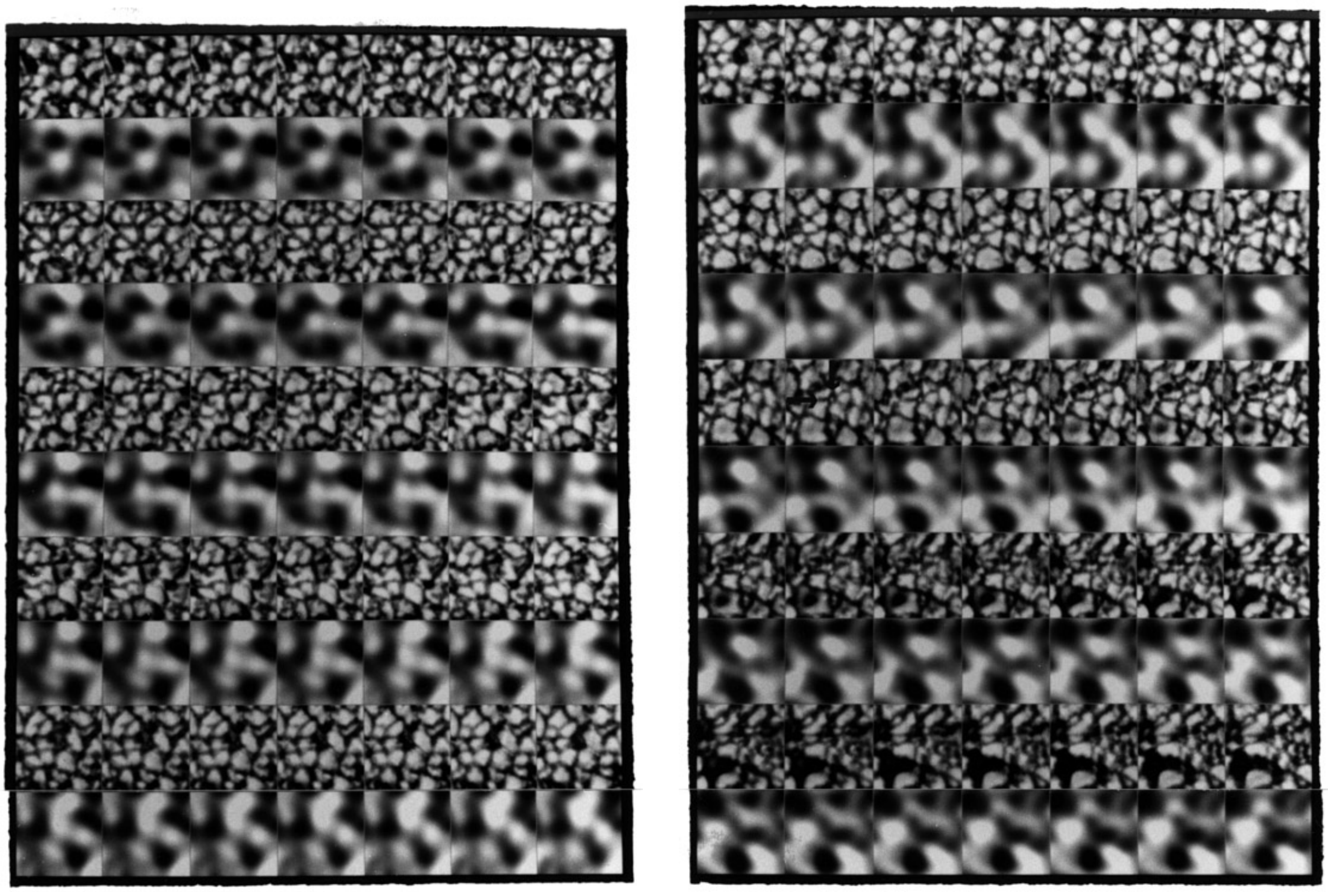

Fig. 5. Time evolution of the solar granulation in a 8 × 8 arcsec field of view, and the corresponding vorticity computed with a spatial window of 1.2 arcsec and a temporal window of 10 min. Arrows indicate the location of the BP formation close to the intergranular hole. The gray scale depicts the vorticity in the range ± 0.0045 sec^{-1}.

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Appendix A: probability of occurrence

We now try to estimate whether the persistence of dark features in the intergranular lanes, over a long period compared to the life of granules, is a process due to chance or not.

If the average size of dark features is n pixels in the case of images digitized at the Shannon step (in order to keep optimal information), the probability P1 of recognizing by chance k pixels of the dark structure after one decorrelation time (i.e. the lifetime of granules which is about 10 min.) may be calculated approximatively using a binomial law:

$$\mathrm{P1} = \sum_{x=k}^{x=n} C_n^x p^n (1-p)^{(n-x)}$$

where p is the filling factor of intergranular lanes (0.34). Hence, the probability Pm o recognizing k pixels inside a dark intergranular feature after m decorrelation times is approximatively Pm=$P1^m$. A result much smaller than unity will indicate that the process is certainly not due to chance and has a real physical significance. We obtain numerically, with n=15 pixels and m=4 decorrelation times (since the lifetime of the dark features is about 40 min.):

P4 = 2.3 10^{-3} for k=7

P4 = 1.0 10^{-4} for k=8

This result suggests that the probability of observing the persistence of dark structures *by chance is quite small* .

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