PROPERTIES OF THE SOLAR GRANULATION

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To the memory of the late Prof. V.A. Krat

Until recently the theory of the photospheric structure has had a modest role. This situation has qualitatively changed with the appearance of the numerical simulations of Nordlund [1], Uus [2], Gadun [3], and others.

The possibilities of 3-D physical interpretation of the observations are limited, remaining qualitative and semiempirical in general. Thus simulations are needed.

The foundation for the fine structure investigations is observation with high spatial resolution, including direct photographs and spectrograms. We already have a set of such observational data now.

A number of facts can be established with confidence, but others are on the verge of observational possibilities at present. The last word still lies in the future. We will examine the facts, analyse them, compare them with corresponding conclusions from modelling, and try to outline the general picture of the photospheric fine structure, as seen by an observer.

We start with the high resolution direct photographs of the solar surface. The two-dimensional brightness field reflects the horizontal structure of temperature, and perhaps also density, in the low photosphere. We are confident now that the brightness inhomogeneities in the granulation are large. At $\lambda = 5000$ Å the RMS $\Delta I_5 = 22$ % . This value was obtained from observations by the Soviet Stratospheric Solar Observatory (SSSO) [4], and significantly exceeds previous estimates, e.g. [5]. At first it was received with some mistrust, but then it was confirmed by independent observations [6], and is in good agreement with predictions of numerical simulations [1, 3]. The mean difference in brightness temperature between granule – porule peaks is 700 K. The largest difference exceeds 1000 K, which is 1/6 of the mean temperature of the photosphere. Thus it is impossible to consider the granulation as a minor fluctuation around the mean level.

Fig. 1 gives an estimate of the true two-dimensional spatial spectrum of brightness deviations at solar disk center, corrected for image MTF of blurring and noise. Here $A(s)$ is the total power density, and

$$s = \sqrt{s_x^2 + s_y^2} = \frac{1}{\Lambda}$$

is the radial spatial frequency. An optical image of the spatial spectra of the granulation was formed from direct photographs of the SSSO, using coherent optical methods [4]. The

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obtained spectrum has a simple form, and can be well represented by two power functions with ascending and descending branches. The spatial period $\Lambda = 960$ km corresponds to the maximum, and is smaller than the main period of the granulation ($\Lambda = 1300$ km) [7]. If we consider the brightness inhomogeneities as temperature fluctuations caused by turbulent convection [9], it is possible to make the conclusion that a considerable part of the inertial and all of the dissipative domains have been in the range of high spatial frequencies ($\Lambda < 300$ km), beyond the resolution that can be attained so far.

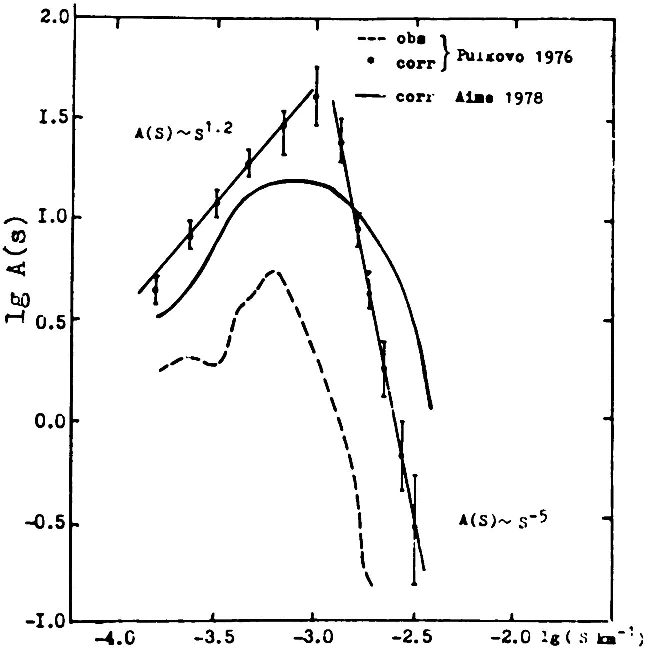

Figure 1. The two-dimensional spatial power spectrum $A(s) = 2\pi\ P(s)$, corrected for MTF, as a function of spatial frequence s. $A(s)$ is the power in frequency intervals $\Delta s = 1\ \mathrm{km}^{-1}$. The power of the constant brightness component is assumed to be equal to unity. The scales are logarithmic. The error bars indicate the uncertainty of the MTF estimate. $\lambda_{eff} = 5000$ Å.

It has been shown that RMS $\Delta I\ (\theta)$ decreases slowly and monotonically from 22 % at disk center to 4 – 7 % at the limb [9]. This result differed qualitatively from previous data, but is in satisfactory agreement with latest results [10]. This reliably determined key fact contradicted the concepts of Wilson [11] and formed the basis for the next empirical models (Altrock, Musman, Nelson, and others [12]). The height dependence of RMS ΔT in such models (taking into account the above-mentioned large value of the brightness inhomogeneities) are given in Fig. 2 (curve 1), together with data from the numerical model of Gadun [3] (curve 2), while curve 3 refers to Wilson's model [11]. It follows from this that the temperature deviations strongly decrease with height from 1000 K at a depth of 25 km to 300 K at a height of 30 km. The vertical temperature gradient in the fine structures may exceed 20 K km^{-1}, and a temperature inversion in the photosphere is possible. The temperature inhomogeneities are absent in the layers higher than 150 km according to all the empirical models [14].

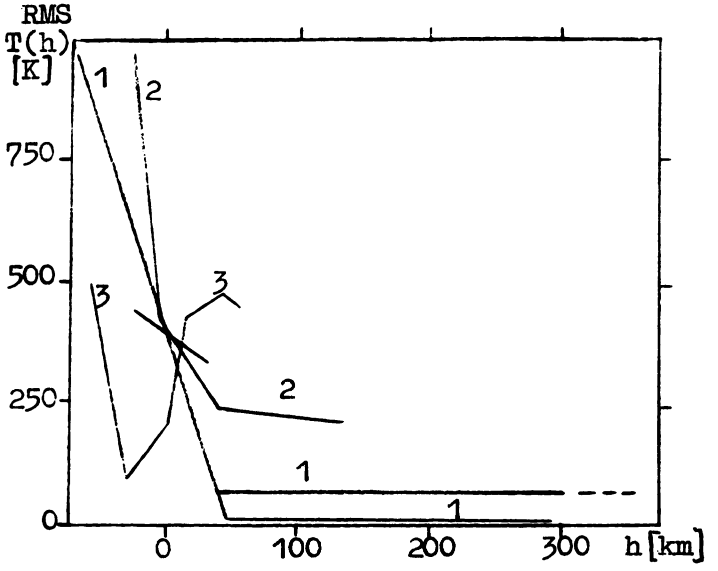

Figure 2. The height dependence of the temperature inhomogeneities. 1: empirical models. 2: numerical model of Gadun. 3: Wilson model. The short line corresponds to the vertical gradient of the mean temperature at $h = 0$ in HSRA.

For the first time fine structures in the brightness were discovered in our stratospheric frames at the extreme limb where the curvature of the limb profile has changed sign, and even 'behind' the limb [4]. They can be clearly seen in the photometric tracings parallel to the limb at the extreme limb $\alpha = 0$, and at a distance of $\alpha = 2.4$ arcsec from it. In the latter case the radial brightness gradient is reduced by a factor of 10. Therefore limb displacements with scales smaller than 3000–5000 km do not exceed 15–20 km, to result in brightness inhomogeneities with RMS $\Delta I_5 = 4 - 7$ %. These fine structures were unexpected and interesting. According to generally accepted concepts the length $\Delta l = 1000$ km along the line of sight corresponds to $\Delta\tau_5 = 0.05$ at the effective height in the photosphere by the limb ($\tau_5 = 0.003$). In this case $\Delta T/T \approx 0.2$ at the limb. We expect that 20–40 such elements with opposite sign of the fluctuation should occur along the line of sight. In this case, however, the contrast in the image must be strongly reduced. The detailed analysis of Lites [15] gives no explanation of this phenomenon. The structure at the limb can give evidence for the existence of a considerable variance in the temperature and, possibly density at heights of about 350 km. There are reasons to look for strong inhomogeneities in the region of the temperature minimum too ($h = 500$ km).

The existence of the structures at the extreme limb seems to be of fundamental importance for our knowledge of the photosphere. No doubt independent verification of it is necessary.

We may consider the photospheric brightness field in terms of random fluctuations. But it is not 'purely random'. It is a non-Gaussian random field, different from a Gaussian one through the existence of substantial inner bonds and good organization. This is the basis for the morphological and morphodynamical approach to such fields, with spatial-temporal predictions that can be more effective than Wiener stochastic extrapolation.

For an estimate of finer peculiarities of the brightness field an excursion analysis of a random field has been made [16]. If the brightness is higher than a given level we have an upwards excursion, if it is lower, a downwards one. The selected brightness level plays a special structural role in our model. There are only upward excursions above this level and downward ones below it in the field. We call it the starting level or starting plane, because both kinds of excursions start from it. It is essential that this starting level is significantly lower than the mean level of the photospheric brightness (by 4.5 –10 %).

The photospheric brightness field may be well represented as an ensemble of two-dimensional, separately connected brightness pulses of both signs, upwards and downwards from the starting level [17]. This field differs significantly from a gaussian one. We will identify bright pulses from the starting level with granules, dark pulses with porules. The term 'porule' was introduced by Rösch (1959). One granule may contain several maxima of higher brightness forming a 'subline' structure. The characteristics of granule and porule ensembles are different, but there is no essential topological distinction between them. Only few granules have darkness in their centers, as mentioned by Kitai and Kawaguchi [19]. This tendency probably becomes stronger after correction for blurring, but its real existence is questionable. The precise, conceptual definition of these two kinds of elements allows us to distinguish single granules as structural elements on the isophotal maps and photographs, and to estimate granular areas with high accuracy. Previous identifications of granules with maximum brightness have a considerable uncertainty. Our model of the brightness structures is illustrated in Fig. 3.

The proposed model is in good agreement with the real brightness field and its dynamics. It would not be successful to represent it as a gaussian field, or as an ensemble of some kind of local bright formations, separated by a multiconnected infinite dark grid of intergranular lanes.

The mean size of the granules is 700 – 800 km, but the largest ones exceed 2000 km.

The perimeter – area connection for granules has been investigated. Mandelbrot has pointed out the importance of the dependence between $\lg(s)$ and $\lg(p)$ as a characteristic of an ensemble of structures [20]. In the linear case $\lg(p) = \lg(a) + (D/2)\lg(s)$, where D is the fractal dimension. $D = 1$, if the shape of the elements is the same for different sizes.

This dependence for granules was first determined by Roudier and Muller [21] and is given in Fig. 4 (dots and thicker line) together with our data (crosses and thinner line). Both determinations are in good qualitative agreement with each other. There are two straight and distinct branches with a sharp break between them around a granule size of 1000 – 1400 km. The fractal dimension is constant for each branch. For $s < 10^6$ km^2, $D = 1.2$. The indentations of the granular boundary lines grow strongly for $s > 10^6$ km^2 ($D = 2.2 - 2.5$). Such a peculiarity needs an explanation. We have however not discovered any morphodynamical peculiarities connected with this break.

The main elementary evolutionary events which cause qualitative changes of a granule are fragmentation into two or several granules, and merging of two or several granules. They are sophisticated processes. It is impossible to consider that large granules are only fragmented, while the small ones are only merging. The birth of new granules and their fading away are five times less frequent than the other events. During the intervals between such events the granules remain qualitatively unchanged. At this stage of qualitative invariability they exhibit a tendency of decreasing their area with time instead of increasing it as supposed

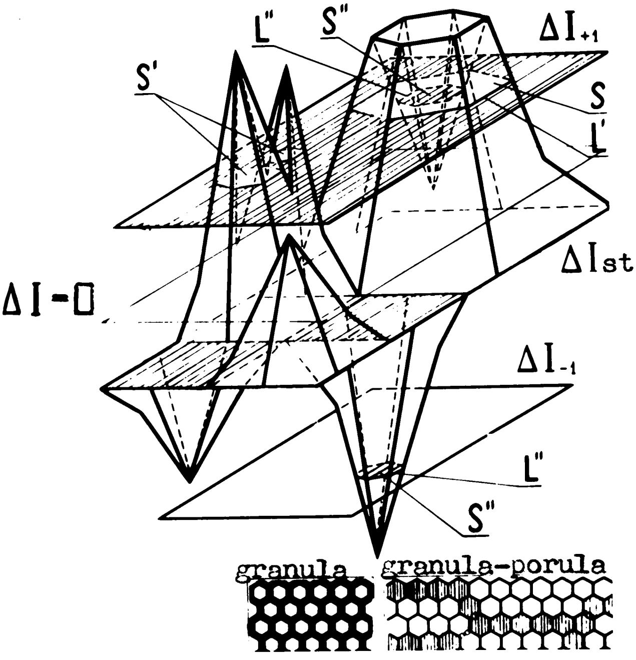

Figure 3. Sketch of the morphological model of the granular brightness field.

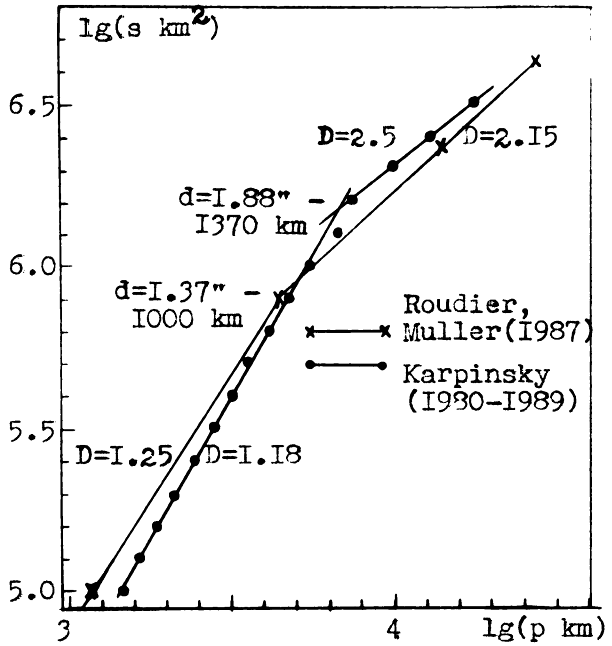

Figure 4. The relation between the perimeters of granules and their areas (in logarithmic scale).

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earlier [22]. The corresponding lifetime of a granule as an individual structure is 5 – 6 minutes, in agreement with the estimate in [23].

The evolution of the granules differs qualitatively from the scheme of birth, growth, and fragmentation into several independent granules, which then are expelled and fade away.

There are reasons to distinguish a subset 'dot granules' with diameters smaller than 200 km (0.3″) and high brightness peaks. Their number is 30 % of the total number of all the granules, but they occupy less than 2 % of the total area. The mean distance between them is about 4″, although their distribution over the surface of the Sun is quite irregular [18, 4]. The relation between these objects and small magnetic fluxtubes is a very interesting subject.

Our data do not clearly reveal the predominating role of exploding granules, mentioned by a number of authors [24, 25].

The brightness inhomogeneities in the continuum and spectral lines are quite different from each other, as noted by Evans [26], Krat [27], Evans and Catalano [28]. The dependence of the correlation coefficient $r(\bar{J}_l)$ between the brightness in the continuum and at various levels of intensity inside the spectral lines is given in Fig. 5. It is assumed that the mean continuum intensity is unity. No significant differences in this dependence between various spectral lines were discovered, including lines with different sensitivities to the magnetic field.

The map of the brightness in a vertical cross-section is shown in Fig. 6. The unshaded areas correspond to an excess of emission, the shaded ones to a deficit. Because the height scale has been magnified twenty times with respect to the horizontal scale, the inclinations of the boundaries between the bright and dark structures are distorted. In reality they are inclined at large angles to the vertical (more than 80°). The brightness inhomogeneities at various levels of intensity in the Fe I 4690.1 Å line are illustrated. For this we only use inhomogeneities of the source function, assume LTE and the Eddington-Barbier approximation, and that the level with $\tau = 1$ has a constant geometrical depth. We are of course speaking about a basically qualitative picture.

It is evident that the brightness structures are fundamentally three-dimensional and nonuniform over height scales of less than 70 km. They differ from earlier suggested patterns of thin layers with slow decline towards the horizontal plane, or from mushroom-like, pancake-like structures, by the variety of their shapes and their complexity.

A second alternative model has also been considered. It is assumed that only deviations of the line absorption coefficient change with height, while the source function inhomogeneities are instead constant over the region of line formation for a given point on the solar surface.

These two opposite models show temperature and possibly also density inhomogeneities, which manifest themselves in brightness. Their typical vertical size is an order of magnitude smaller than the horizontal size, i.e., less than 100 km. The width of the emission contribution function is about 200 km. It seems that such small-scale changes with height should not be observable so clearly. Like the inhomogeneities at the extreme limb, they should not be seen. This is the second 'hot topic'.

Now let us turn to spatially resolved motions along the line of sight in the photosphere. The velocities manifest themselves as displacements or wiggles of spectral lines. The RMS $V(h)$ is given in Fig. 7. The data of Pravdjuk [29] without correction for blurring (line 1), the estimates of Durrant et al. [30] (line 2), as well as those of Bässgen and Deubner [31] (lines 3, 4) for various versions of the correction are presented here.

The general conclusion is that considerable velocities are typical over the whole range of heights from 50 km to 450 km, with small variations. The typical sizes of the velocity and

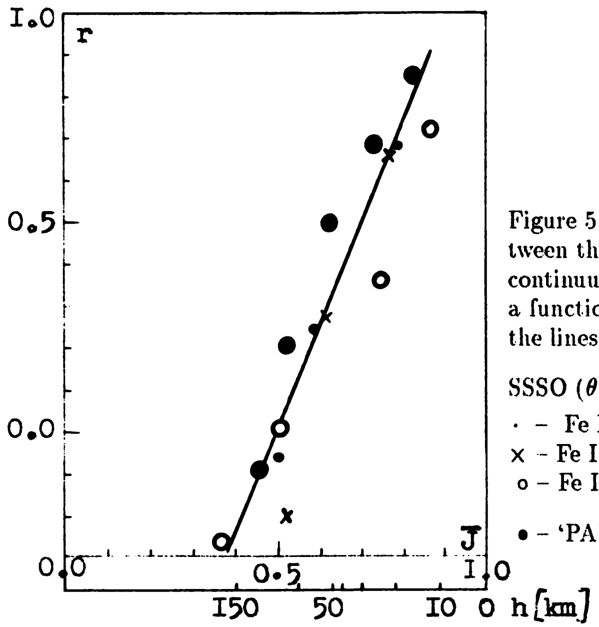

Figure 5. The coefficient of correlation between the brightness inhomogeneities in the continuum and in various spectral lines, as a function of the level of mean intensity in the lines.

SSSO ($\theta = 15°$):

· – Fe I 5250 'magnetic line'

× – Fe I 5247 'magnetic line'

o – Fe I 5216 'nonmagnetic line'

• – 'PAMIR' ($\theta = 37°$)

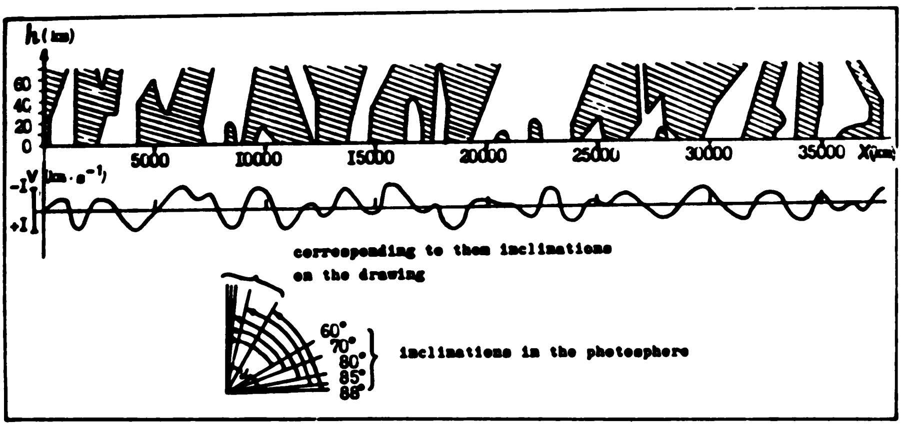

Figure 6. Map of the brightness (emissivity) for a vertical section of the photosphere, and the corresponding vertical velocities. The transformation of real angles in the photosphere to those in the figure is shown in the bottom of the diagram.

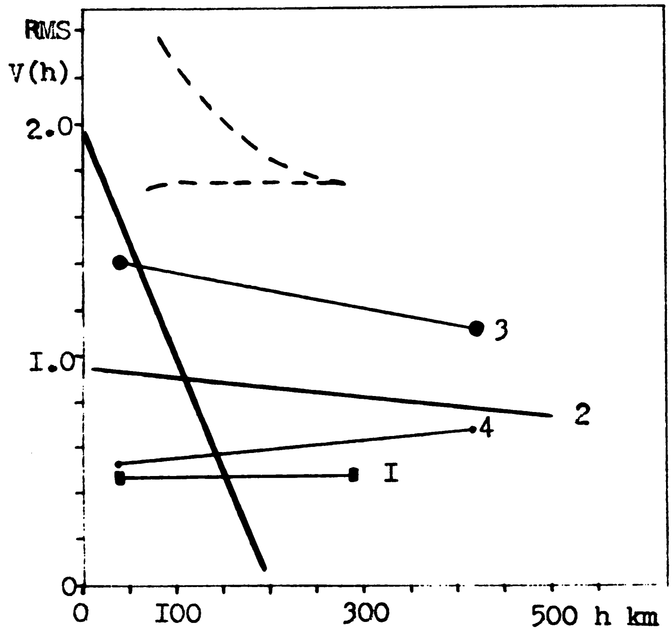

Figure 7. Height dependence of the RMS velocities. 1: Pravdjuk (1982). 2: Deubner, Mattig, Nesis (1979). 3, 4: Bässgen, Deubner (1982). Thick line: Keil (1980). Dashed line: Total non-thermal velocity (Kostik, Kondrasheva, Sheminova, 1981-85).

brightness inhomogeneities are similar [29]. An upward expansion of the structures is not found.

The corresponding results of Keil [32] are also given (thick line), indicating that vertical velocities are absent above 200 km. This qualitatively disagrees with the other results.

The height dependence of the total non-thermal velocities obtained by the Kiev group [33] is also shown (dashed line). The spatially unresolved velocity accounts for a considerable part of the total velocity. This follows from the spatial spectrum (Fig. 1) as well.

The coefficients of correlation between the Doppler velocities in the low photosphere (height 100 km) and in higher layers have been estimated [29]. The height dependence is given in Fig. 8. We use the effective heights for the Doppler measurements, which in a first approximation correspond to the centre of gravity of the depression contribution function of the Unsöld-Pecker form.

It is possible to speak of perfect correlations between the velocities for heights up to 240 km. This fact was discovered by Pravdjuk [29] and Durrant and Nesis [34], and has been confirmed later [35]. Hence the velocity structure has the shape of a set of vertical, parallel columns in this part of the photosphere [34, 7]. On the other hand the velocities at these heights should vary greatly according to the 'oscillatory' or 'convective' concepts of the photospheric velocity field [34].

This correlation, however, drops rapidly above 240 km. At a height of 275 km it is only $r = 0.5$. This was found from the behaviour of the displacement of the CN 3882.6 Å line [29, 36] at various levels of the intensity inside the line, and was confirmed using the Na

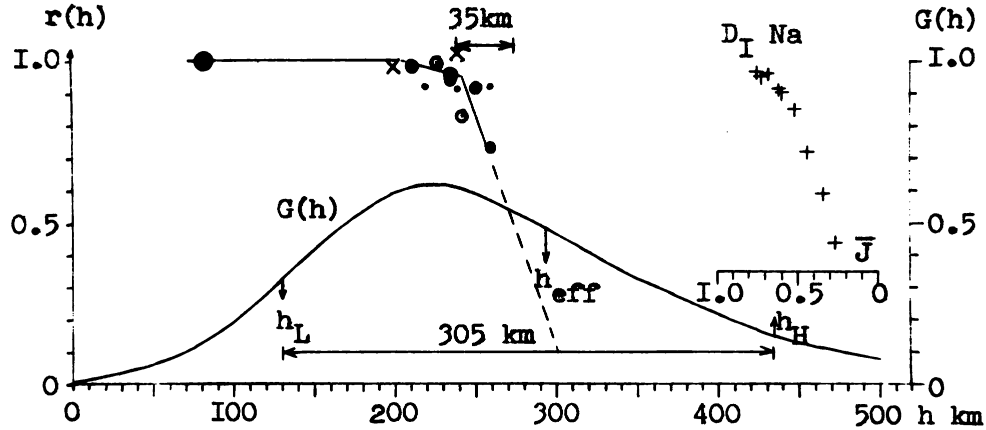

Figure 8. The dependence on height of the correlation coefficient between the Doppler velocities in the low photosphere (h_{eff} = 100 km) and at different height levels h.

D$_I$ line. The height scale for this drop of the correlation is much smaller than the width (≈ 300 km) of the CN contribution function (illustrated at the bottom of Fig. 8). In this case the calculations show that the correlation coefficient should not be smaller than 0.96. The disagreement with the observation is obvious. The given arguments are of a qualitative nature, but it seems to me that this is another 'hot topic' in our concepts of the photospheric structure.

The mentioned qualitative difference between the structures of vertical velocities and brightness should lead to a reduced correlation between them [37, 38]. The coefficient of correlation between the total velocity at a height of about 100 km and the brightness in the continuum is $r = 0.54$. For this value the completely uncorrelated additive component is 1.6 times larger than the correlated one [39]. The differences are due to fine structures to a considerable degree [53]. For fine structures only with $\Lambda_x < 2000$ km, $r = -0.66$ [39]. The 5-minute oscillation does not contribute here. The coefficient of correlation between velocity and brightness in spectral lines quickly goes to zero when moving towards the line centre, and then changes sign to positive. Note that minus corresponds to an upward motion of the bright elements. The coherence spectrum (linear coherence, similar to the coefficient of correlation) drops considerably (to 0.5 and less) for $\Lambda_x < 1750$ km [7], and in particular for $\Lambda_x < 700 - 1000$ km [40, 41, 42], although for 2000 km $< \Lambda_x <$ 4000 km the coherence is high.

It is possible that a correlation between the vertical velocities and the brightness exists in the lower layers of the photosphere ($\tau \geq 1$) [42], but that it is disturbed considerably at heights above 50 km, for the photosphere as a whole, in agreement with the results of numerical simulations. Decorrelation may be the result of turbulence, internal gravity waves, or inhomogeneities of non-convective nature. It is difficult to separate and estimate the relative roles of these effects now [42].

Considerable disagreements between the results of various investigators often occur in current granulation research. In a number of cases these discrepancies may be the result of errors or observational difficulties. In some cases, however (and this is very important), they may reflect real variations in the photospheric structure. Abnormal granulation and filigree were discovered in the beginning of the 1970s [43].

Changes of the granulation with the solar cycle have been established [44], including their connection with the radio emission [45]. Distinctions between the fine structures inside supergranules and at its boundaries have been determined [24, 46], and mesogranulation has been discussed [47, 48]. Fast, large-scale changes of the granulation ('perestroika' of its structure) have been discovered on the SSSO photographs. The number of granules change by a factor of 1.5 and their mean area by a factor of 2 during 5 minutes. This change is coherent over an area of at least 5×10^8 km^2. The general restructuring of the ensemble as a whole happened within the lifetime of its granule elements [49, 50]. This non-stationarity demands a stricter approach in comparison with the individual definition of the granular characteristics.

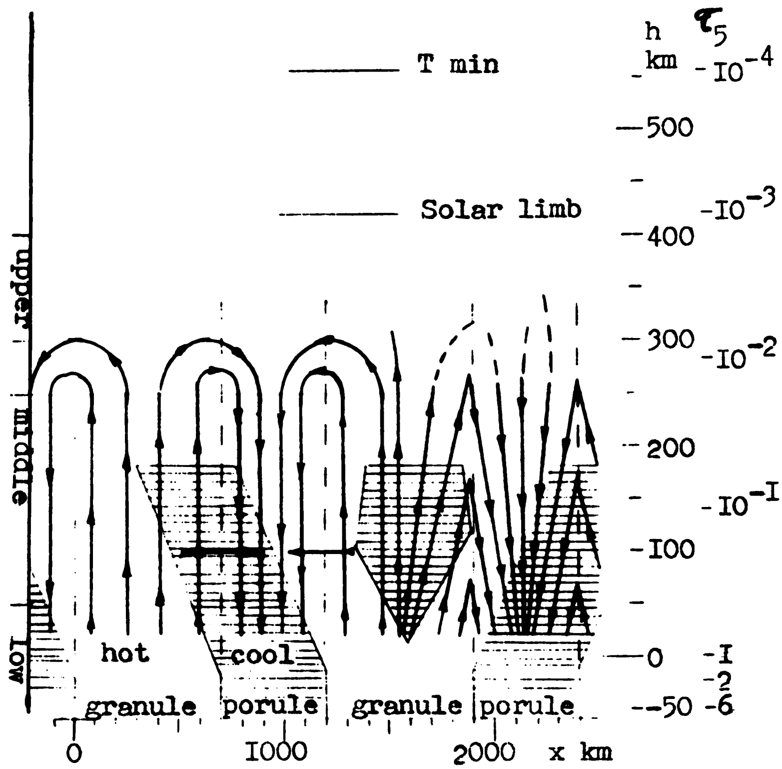

Figure 9. Illustration of the structures and the movements in the photosphere.

We present in Fig. 9 such a scheme of structures and movements in the photosphere. We may distiguish four layers: the low photosphere up to a height of 50 km, the middle (h = 50 – 240 km), the upper photosphere above 240 km, and the temperature minimum region.

In the low photosphere the vertical temperature gradient is high, and the density is almost constant. The velocity and temperature structures may spatially coincide here. The concept of 'granule' is reasonable here for the designation of some indivisible, three-dimensional

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structure. Outflow of matter from a granule through its motionless boundary takes place. It is accompanied by a cooling of $5 - 10$ K km^{-1}. This feature is well reproduced by the numerical models. The observed structure is closely described by laminar convection here.

This unity is violated in the middle photosphere. It is impossible to speak of unique cellular patterns there. Vertical, cylindrical velocity structures are typical, and the horizontal outflow does not change this. The brightness structures, however, do not coincide with the velocity structures. There is no correlation between them.

The transition to the upper photosphere occurs where the column velocity structure is breaking up. Here and in higher layers there may be very significant inhomogeneities of non-convective origin, variations of the absorption coefficient, density, and magnetic field. This is in accordance with the picture proposed by Nesis [51]. So considerable small-scale inhomogeneities are characteristic of the whole photosphere, not only of its lower part, directly adjacent to the convection zone. The sophisticated structure of the middle photosphere arises due to the convection, but is only indirectly connected with it.

The nature of the inhomogeneities in the high photosphere and the temperature minimum region is probably not convective [51]. The non-thermal energy, which produces non-equilibrium conditions in the chromosphere and corona, may be generated here [52].

The density drop between heights $h = 100$ km and $h = 240$ km is about a factor of 5, according to HSRA. In this case the cylindrical velocity structures without upwards expansion must smooth out density fluctuations in the middle photosphere. The density fluctuations at height 250 km should be greater. If this is so, we have no constant downward outflow (effect of 'the pipe being full of holes'). This downward outflow without expansion has not been observed directly yet.

The hydrostatic equilibrium may be violated under these circumstances. Hydrostatic equilibrium is postulated for all photospheric models, but as far as I know, we have no direct observational proof that this assumption is valid.

It is possible that we may be able to explain through such effects the observability of the fine structure at the extreme limb, as well as the strong reduction in the correlation between the brightness in the continuum and the spectral lines and the velocities over small height differences.

Let us in conclusion formulate some general problems:

1. The nature, meaning, and significance of the inhomogeneities at heights above 200 km.
2. The role of magnetic fields for the mere existence of the photospheric fine structure.
3. The ultra small-scale, subgranular structures, and their role for the generation of turbulent viscosity and magnetic diffusion.
4. It seems to me to be important to learn to predict the granulation pattern over 15 minutes in time, for 10 000 km in space. Some possibilities for this exist.
5. The change in the nature of the granulation structure in space and time. The connection with the large-scale and global structures and characteristics.
6. It is necessary to learn to diagnose better from the observations the inhomogeneities of the temperature, density, macro- and microturbulent velocities, and, of course, the magnetic field in the three-dimensional photosphere.

The granulation is a large, natural, organized system. It is not so hopelessly sophisticated as active solar features. There is hope that we may be able to understand it in general as well as in detail, and make contributions not only to science about the Sun, but also to the understanding of the nature of dissipative structures — one of the most important problems of our time.

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