PADEU
PADEU **15**, 59 (2005)
ISBN 963 463 557

Dichotomic model for describing the solar granulation dynamics

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Abstract
In the present communication, we describe a simple model for the observed solar granulation. The proposed model is a phenomenological one, and describes the dynamics of granulation as complex changing patterns observed on the Sun's surface. Based on some observed facts, we describe the variability of the granules form and the statistics observed, as a continuous process of "splitting" each granule in two pieces, in a roughly constant area ratio. This process is named a dichotomic process, and produces in time, granules of different forms and dimensions. Simulating such kind of dichotomic "fragmentation" of the granules, starting with a given initial distribution, we can obtain the distribution of the granules area at a given moment of time that can be compared with the observed statistics.
Keywords: *Solar granulation, dihotomic model, fractal interpretation*

1 Introduction

Solar granulation is a common feature observed inspecting the Sun surface. Its mosaic, grainy structure is easy to observe in images obtained with a high resolution. The origin of granulation is complex but mainly is due to the convection of the fluids from the depth to the vicinity of the observed surface of the Sun. Many aspects contribute to the feature observed: the temperature gradients in the convection zone, the (differential) rotation of the Sun, the magnetic field from the vicinity, the composition of the fluids (plasmas) and the mixing processes, and so on.

Extremely complex simulations of magneto-hydrodynamics near the Sun surface to describe the convection and to understand the granulation are far to be satisfying (Berger & Scharmer , 1999).

In the present communication, we describe a much simpler version of a model for the observed granulation.

The proposed model is a phenomenological one, and describes the dynamics of granulation as complex changing patterns observed on the Sun's surface. Based on some observed facts, we describe the variability of the granules form and the statistics observed, as a continuous process of "splitting" each granule in two pieces, in a roughly constant area ratio. Various hypotheses for the fragmentation mechanisms and a given initial distribution can be used, in order to choose the best one. We will show that such a simple model can reasonable describe some of the observed facts, giving some hints for understanding solar granulation.

Convection is the dominant mechanism of energy transport in the envelopes of the Sun. The flow in the free convection is driven by buoyancy forces, which are induced by a temperature gradient between the lower and upper boundaries of the plasma in a gravitational field. The convection zone is an extremely dynamic layer form of the Sun, that shows itself in high resolution images, as a collection of relatively small, variable form, patches named granules (Fig.1), one division equal 1000 km). At the centers of granules hot solar gas rises and radiates its heat rapidly into space; the gas is then diverted horizontally, and sinks back into the Sun in the darker intergranular lanes. The sizes of the granules range from approximately 250 km (the limit set by the telescope and the Earth's atmosphere) to more than 2000 km with an average diameter of 1300 km. Lifetimes of granules typically range from 8 to 15 minutes. Horizontal and vertical velocities of the gas motion are 1 to 2 km/s.

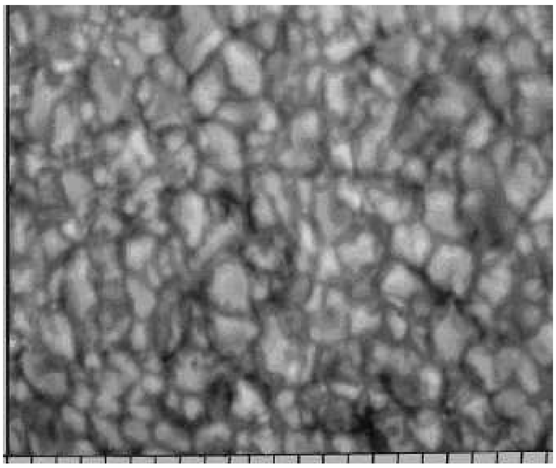

Figure 1: *A picture of solar granules*

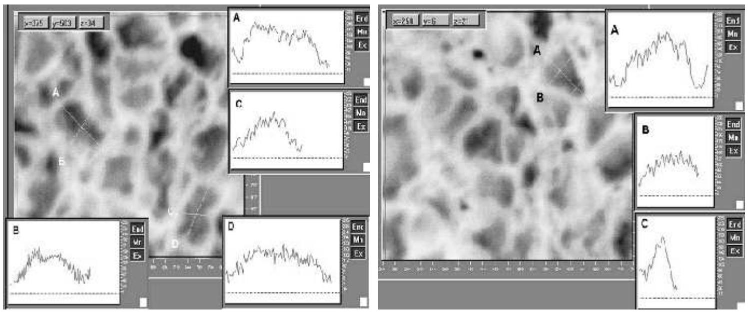

Figure 2: *Luminosity profiles on negative images of the surface*

Examples of such convection pattern in gravitational field can be observed also on Earth, for example in huge fire in the forests.

It is possible to try to describe as precise as it is possible, the dynamics of the fluid circulation in the convection zone, but the huge amount of data needed, and the complexity of equations and conditions are formidable. At least, simulations of this dynamics can be done with limited accuracy, and the results are promising (Brummel et al , 1995), giving us a much confident image of the convection. The result obtained from simulation could be described as a "forest" of jets of fluids that comes from inside and ends at the surface, cooling the fluid, which after is sinking back in the depth of Sun.

2 The model

2.1 The morphology of granules

The variation in luminosity and the form of the end part of the columns (the granule) shows variation in space and time, and defines (in a loosely speaking way) the boundaries of granules. Our computer image analysis of granule luminosity could be seen in figure 2 (luminosity profiles on negative images of the surface). From this analysis we can conclude that a very sharp and well defined boundary of a granule is difficult to find. However, having high-resolution images it is possible to describe some statistical characteristics of the granules.

Very high-resolution pictures (0".25 - Pic du Midi Observatory) used for analyzing solar granulation using computer-processed images found that the distribution of the number of granules increases continuously towards smaller scales. This means that the solar granulation has no characteristic or mean scale. Nevertheless, the granules appear to have a critical scale of 1".37, at which dramatic changes in properties of granules occur; in particular, the fractal dimension changes at the critical scale (Roudier et al , 1991).

2.2 Fractal analysis of solar granulation

The study of turbulent phenomena has been a demanding task in astrophysics. The photosphere of the Sun is one of the few places in astrophysics where turbulent motion could be, in principle, observed directly. The high spatial resolution, which can now be attained, and the development of new ways to describe and analyze chaotic systems, i.e. the concept of fractals changed our possibilities, today.

We made fractal analysis of some images in order determine the fractal dimension (D) of the granulation filed (Munteanu et al , 1994). The method used was the box-counting one. Determination of the fractal dimensions of the solar granules, using luminosity analysis has some difficulties because of the uncertainties of the granules boundaries. The results of our work reveal that there are variations of the fractal dimension, if we analyze pictures of granules in regions in which exists sunspots, (D = 1.37) or pictures in regions without such features (D = 1.81). The same, large distribution of fractal dimension for granulation was obtained by Brundt et. al (Brundt et al , 1991), but without a correlation to the regions on the Sun.

2.3 Granule statistics

Being interested in the granule structure and their geometry and dynamics, we focused on the image analysis and recognition of patterns, and on the statistics of the granules population. We used images obtained by The Swedish Solar Vacuum Telescope. Almost all the conclusions described here were drawn using this source.

For the statistics of inter granular distances, we made extensive measurements on a large surface of the Sun. Radial distribution function (number of granules versus inter granular distance) was computed from the list of all distances found on the image, measured and processed using a special design computer code. The "position" of a granule used for computing the distances, was defined using different algorithms: the geometrical mean of the roughly ellipsoidal granules, the point of highest luminosity inside the granule boundary, or a simple visual center of the granule. The results obtained for the distribution are practically the same for all methods of finding the position of the granules.

The whole investigated region was divided in 10 rectangular fields, and the radial distribution function of the inter granular distances was computed. The results are presented in figure 3, for nine regions. A striking and unexpected result appeared, without exception: all the distributions show asymmetry. The distribution suggested that a deconvolution of the asymmetric distributions in two symmetric Gaussians could be possible. Figure 4 shows the experimental points (dots), the two Gaussian distributions (green line) and the reconstructed - convoluted distribution (red line).

It is without doubt that the deconvolution works well. If this deconvolution has any physical meaning is another question.

Analyzing the parameters of the Gaussian distributions, it was also evident that the positions of the two maxima are correlated in each investigated region. Such a correlation could be seen in figure . The chart of the region studied is also presented here. The two groups of distributions have distinct average distances between granules. We denoted "line 1" and "line 2" the two distinct distribution found in each region. We can consider that the analysis reveals two distinct "populations" of granules.

Results and conclusions:

The slope of graphs: position of line 1 versus position of line 2 is 1.64 considering all the points (the red line),

The line of slope 2 is shown for comparison (the black line),

The points 1, 2, 3, 5, and 7 are from regions free of sun spots;

The points 6, 8, and 9 are from regions near sunspots; they are the most distant points from the best fit line,

Part of the dispersion of the fitted parameters of the deconvolution could be attributed to the difficulties of assessing the center of the granule from the images.

The whole trend suggests that the two populations could be a result of a splitting mechanism applied to the "mature" granules, that suddenly reduces approximately to half the average distances between granules. This is a statistical inference which we can explain simply using a phenomenological model.

2.4 The dihotomic model

We tried a phenomenological model, namely a dihotomic model. We consider the following scenario:

The grains are in continuous change of form and size. There are moments when grain splits in two smaller grains. The population statistics at one moment contains in fact at least two different populations. The distribution shows after several generations of splitting process an increases of the diversity of grains size.

New grains are added to the distribution, and the small ones disappear. The result is a statistically stable structure of two distinct populations of grains. A simple example of a dihotomic fragmentation and self-similarity could be used as a model for the dynamics of the two populations in equilibrium. The main hypothesises are: constant ratio of division, K, and a conservation of the initial area (or other measure, denoted here by V) at the moment of division. These two hypothesises could be written as:

$$V_0 = V_1 + V_2 \ ; \ K = \frac{V_2}{V_1}$$

To summarize the results, after one division, the parts are:

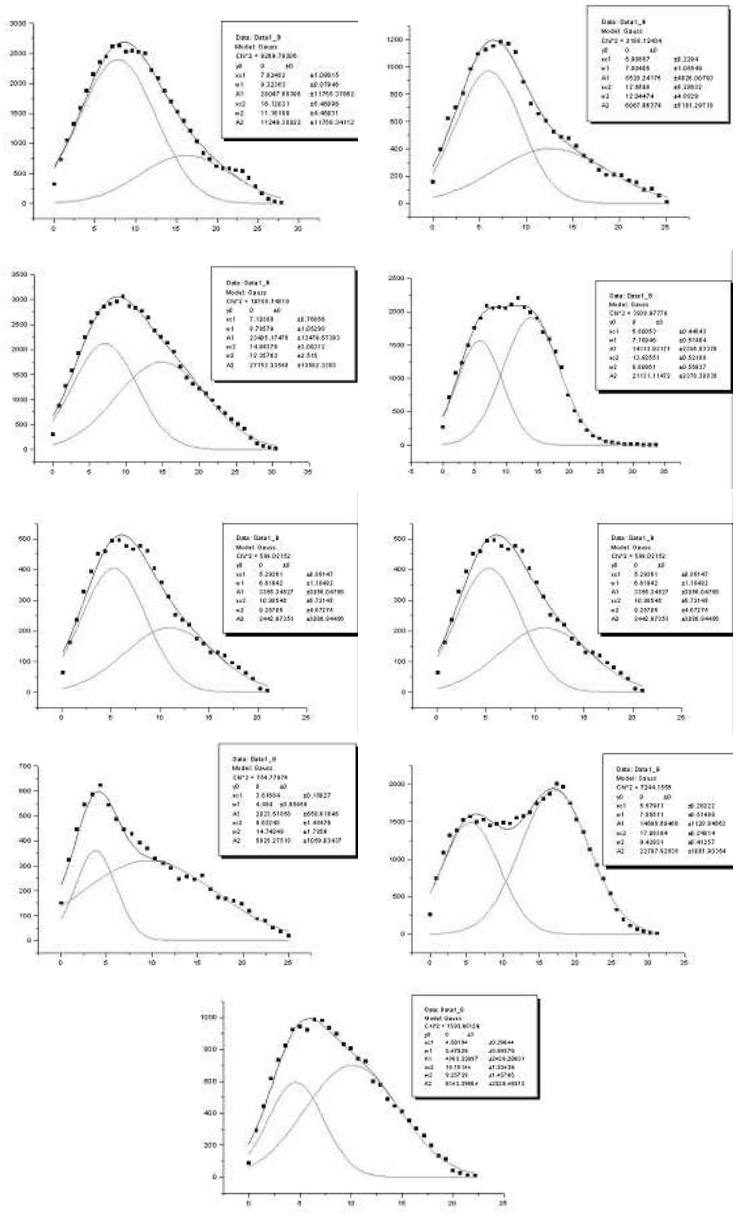

Figure 3: *The computed radial distribution function of the inter granular distances*

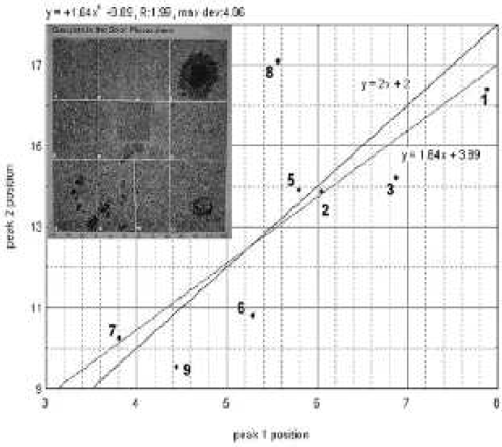

Figure 4: *Representation of experimental points, Gaussian distribution and reconstructed-convoluted distribution*

$$V_1 = \frac{V_0}{1+K} \; ; \; V_K = \frac{V_0 K}{1+K}$$

After n-divisions (generations) the size of p-fragment has:

$$V_{p;n,K} = V_0 \frac{K^p}{(1+K)^n} \; , \; p = 0, 1, 2, 3, ..., n$$

The lowest size are: $V_{min} = \frac{V_0}{(1+K)^n}$ The largest size are: $V_{max} = \frac{V_0 K}{(1+K)^n}$ The difference and ratio are: $d = V_{max} - V_{min} = V_0 \frac{K^n - 1}{(1+K)^n}$ and $r = \frac{V_{max}}{V_{min}} = K^n$; The mean values are: $\bar{V} = \frac{V_0}{2^n}$ and $\bar{N} = 2^n$

Figure 5 shows the distribution after N = 11 generations, with a fragmentation ratio K = 1.6

We can make this process more "realistic" if we add a noise in the fragmentation ratio: $K = K_0 + K_{noise}(t)$, that can be used in computation. The result of such a noise, is a spreading (and smoothing) of the distribution groups (Fig.6).

If the time between generation, splitting and disappearance of the grains is short, just two generations could be seen in the distribution, and the distribution is "smoothed" by the random size of generated grain, and of the moment of splitting. In addition, this could account for the limitation of the maximum size of a grain, explained by this mechanism of splitting. The moment of splitting is probable triggered in the column of the convection tube, by some instability in the flow.

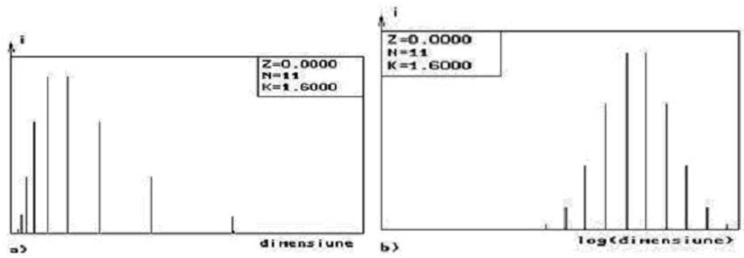

Figure 5: *Distribution after N=11 generations*

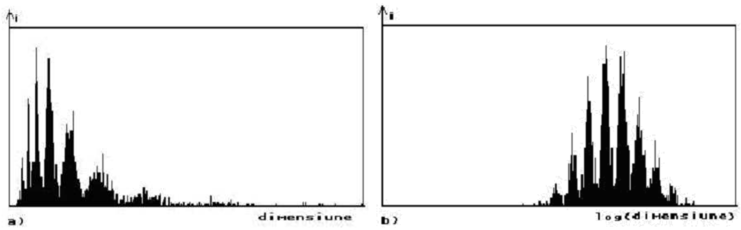

Figure 6: *Distribution groups*

2.5 The dynamics of granules evolution

In order to see if this mechanism could be real, we examined the movie pictures of the granulation dynamics. The series of the images was observed with a fast frame selection system on June 5, 1993, at the SVST (La Palma) in cooperation with G. Scharmer (Stockholm) and G. W. Simon (Sunspot); N. Hoekzema (Utrecht), W. Mhlmann (Graz), and R. Shine (Palo Alto) were involved in the data analysis. Technical data: wavelength 468 ± 5 nm; exposure time 0.014 s; rms contrast (uncorrected) between 7 and 10.6 %. The images were registered, destretched, corrected for the telescope's point spread function, and sub sonically filtered after interpolation to equal time steps. For each frame, both area and total time are indicated.

A sequence of these time-lapse series of the evolution of the solar granulation is represented in figure 7. Qualitatively (this analyze is at the moment under computation, using a special code for pattern recognition and granule characteristic extraction) the above phenomenological model seems to be correct.

3 Conclusions

The fractal structure of the granulation field suggests some self-similar mechanism that acts in the dynamics of the convection.

The simple model of dihotomic self-similar fragmentation could reasonable explain the presence of the two distinct populations observed in the statistics of radial distribution of distances between granules The dynamics of fragmentation, which is revealed in the motion pictures of the Sun's surface, qualitatively confirms the idea of continuously dihotomic fragmentation of large granules.

This model gives a simple phenomenological mechanism that could describe the facts found in the statistics of granules and gives us a hint about the phenomena inside the convection zone. We can make the hypothesis that the convection tube in his upward moving can exhibit instabilities that split the tube, most probable in two adjacent tubes, and a hierarchy of splitting could follow this process.

The assemble of the tubes will exhibit self-similarities revealed in the measured fractal dimension.

Acknowledgement

I we would like to thank prof. Don Wentzel for his suggestions and help in completing the image and to the work of some students involved in measurements: Adriana Durbala, Oana Stere, Constantin Oprea and to Alex Curutiu for producing the computer codes used in automatic processing of the images

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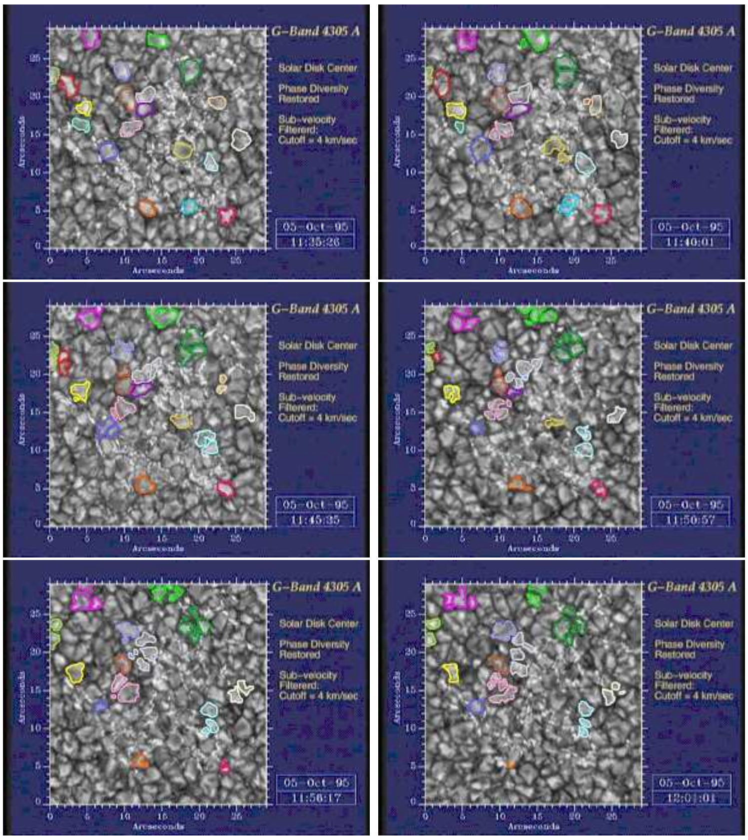

Figure 7: *Movie pictures of the granulation dynamics*