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GRANULATION PROPERTIES IN DOT IMAGES FROM SOLAR MAXIMUM TO MINIMUM

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Abstract. DOT granulation filtergrams in the G-Band from solar maximum to solar minimum (1999 to 2007) were investigated for changes of granulation properties like areas, perimeter, fractal dimension, cell sizes, and life times. Granules seem to become larger during solar minimum, whereas the distances between the granule centres stay constant. Nonetheless, the uncertainties are very high.

Key words: Solar cycle - granulation

1. Introduction

Solar cycle dependencies of the granulation have already been investigated by Macris *et al.* (1984), Muller and Roudier (1984a), and Muller and Roudier (1984b) using Pic du Midi observations. But in these works problems like inhomogeneous data sets, image degradation, and manual granulation identification led to uncertain results. Despite of that the authors found in all of these works a decrease of the mean distance between granule centres of about 20% from solar minimum to solar maximum. The same result was found by Dialetis *et al.* (1985) in data sets from 1966 to 1978. In Muller (1988) the number of granules increased towards the solar maximum, but this result was very uncertain. Digital images from 1978 to 1991 taken at Pic du Midi have been used by Saldaña-Muñoz *et al.* (2004) for statistical investigations by power spectra. From this work the authors conclude that there are more small granules during the solar minimum, which is contradictory to the previous authors. In Muller *et al.* (2006) the same data set from 1978 to 1991 was analysed for contrast and granule size, as a result the contrast decreased with increasing solar activity and the size of the granules seemed to increase.

Due to the inhomogeneity of the time series, digital imaging was just in development, the errors of such investigations were very large, which leads to these contradictory results. Since the early 1990s CCD devices have been available with high resolution and fast image acquisition. With such devices it was possible to take long time series at high resolutions containing a lot of information for good image statistics.

One instrument of high quality, that was not mentioned in Roudier and Reardon (1998) for investigations of the solar cycle variations is the Dutch Open Telescope on La Palma. This instrument is observing the Sun at high digital quality since the 1990s it was decided to use time series of solar granulation filtergrams from there. The online data base offers time series of the solar granulation in various wavelengths from 1998 on up to now (`http://dotdb.phys.uu.nl/DOT/`).

2. Data and Methods

The data sets range from 1999 to 2007, covering the time span from solar maximum to solar minimum of cycle 23. During the data sets from 1999 to 2001 the sunspot number was between 137 and 185, whereas in the last sets the index was about zero (see Table I). All data sets were obtained in the G-band which was the only wavelength available over the whole time span. One drawback of this wavelength range is the existence of the bright points, which show up as small bright granules at super-granular borders. The data sets all have the same digital resolution of 14.1 pixels per arcsec, they are all near the disc centre, and only subareas without pores or spots are taken into account. The length of the time series varies between 19 and 254 images and the time step between the images ranges from 12 to 30 seconds. Each image is obtained via the speckle method and the time series show therefore an outstanding quality. All data sets were k-Ω filtered with a cut-off velocity of 7 $\mathrm{km\,s^{-1}}$.

For selecting singular granules a Fourier filter according to Roudier and Muller (1986) that amplifies patterns of a certain size was used. In this work structures from 0.5 to 2.25 arcsec in diameter were enhanced and then selected by a simple threshold filter. Then each granule was identified and given its own number, granules touching the border of the images were removed. From these granules areas and perimeters were obtained by counting the pixels with the same colour for the areas and counting border pixels for

Table I: The 25 data sets used for this investigation. SSN is the international sunspot number reported by the Solar Influences Data Analysis Center (SIDC).Types: *QS* ... quiet sun, *AR* ... active region, *Fil* ... below filament. Subimages were used if there were spots or pores in the set.

Date	#	Type	SSN	Date	#	Type	SSN
19991021	148	AR	137				
20000923	65	AR	169				
20011017	19	QS	154	20011019	198	AR	161
20011020	178	AR	185				
20020430	54	AR	87	20021208	107	QS	104
20030502	155	QS	77	20030616	178	QS	63
20030714	38	AR	114				
20040927	137	QS	21	20040928	135	Pore	16
20041015	78	Fil	13				
20050911	142	QS	46	20050914	151	Fil	58
20051019	142	QS	16				
20060504	162	QS	36	20060629	125	QS	30
20060703	120	QS	18	20060923	177	AR	9
20070412	180	QS	0	20070520	46	QS	25
20070813	134	QS	8	20070907	109	QS	0
20070926	196	QS	0				

the perimeters. Distinguishing between granular and intergranular regions is also done by this method.

Distances between granules were obtained via Delaunay triangulation. From each granule centre a line to the next granule centre is drawn. Lines do not intersect. Each granule can have between 2 and more than 8 neighbours (Figure 1, left).

Cell sizes are calculated with the watershed method. In nature water from precipitation flows down from higher regions into valleys or basins. The points separating two basins are called watersheds. The same can be done with intensity images, where intensities are assumed as heights. Each region, where the water accumulates in the same basin is defined as one cell. For this purpose the intensities are inverted: a granule is the basin and its surrounding inter-granular region becomes part of the cell (Figure 1, right).

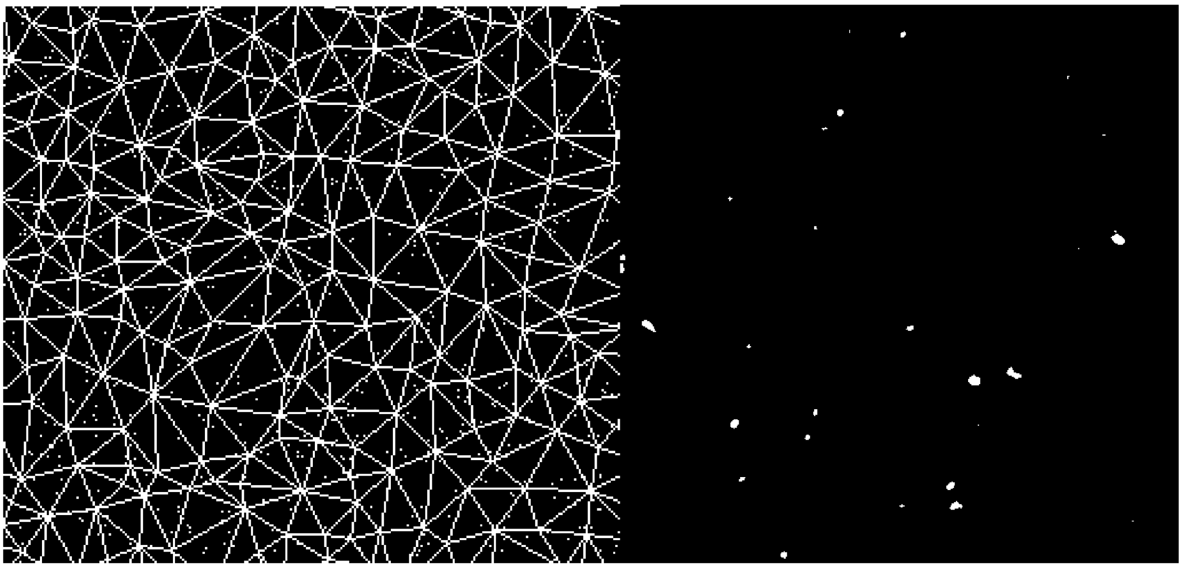

Figure 1: Left: Delaunay triangulation – the granule centres are connected with lines that do not intersect. Right: Watershed method - granules are interpreted as valleys and intergranular lanes as mountains, like in nature precipitation gathers in basins or valleys. Complex granules can have more than one local maximum and split therefore up into more cells.

Very big and complex granules can consist of more than one cell, since there is more than one local maximum (in this case minimum).

The *fractal dimension* is the logarithmic area perimeter ratio, which is 2 for ordinary shaped figures i.e. the area increases with the square of the perimeter. For fractal figures the parameter can be higher than 2, which means that the perimeter grows faster or is not proportional to the square root of the area. Plotting granule areas against perimeters shows a kink in the distribution. The position of this kink marks the size from which onwards granules become more structured, or below which granules are circular in shape. If there was the same number of circular granules distributed over all the area range, there would be no kink. Big granules are more structured and ramified and produce therefore this kink in the plot.

The *lifetimes* of granules are obtained from a string search algorithm, which tries to find for each granule a follower and a predecessor, i.e. the time-series is searched forwards and backwards. If there is no follower or more than one follower the end of the granule is defined. Therefore these times are not real lifetimes. The lifetime of a granule is only a question of definition, looking at granulation movies shows that there are granules that

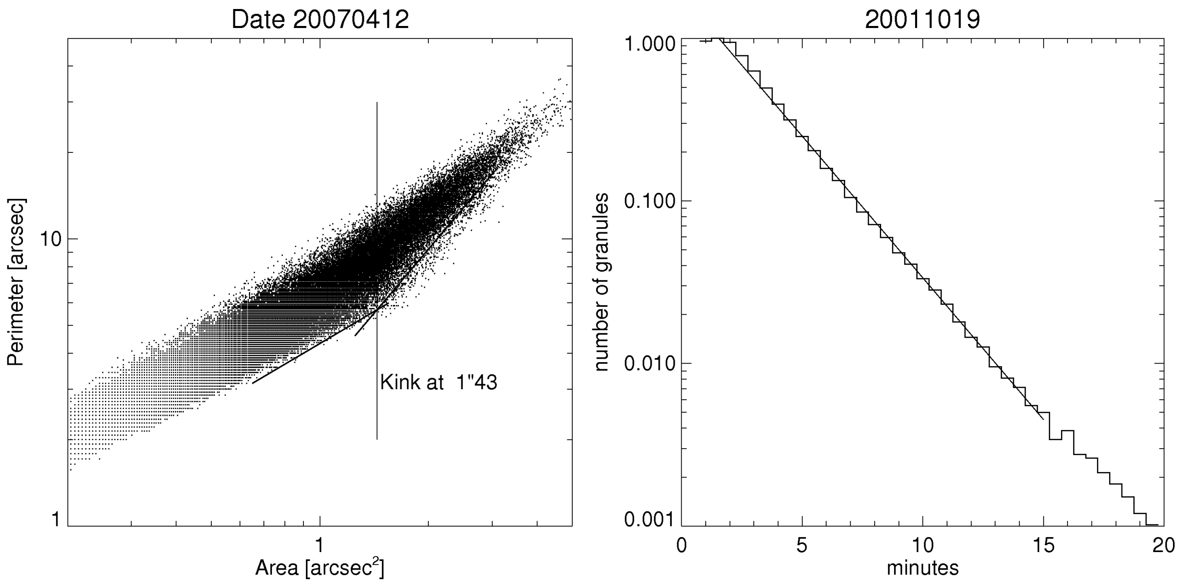

Figure 2: Left: Fractal dimension – large granules have higher fractal dimensions, because they are more structured than the small circular ones. The upper envelope has a constant slope, this slope defines the maximum perimeter for each area. The lower envelope would show a constant slope, if all granules were circles. Right: Lifetime - from the lifetime histogram a *decay time*, which corresponds to the slope of the curve can be obtained.

seem to live for hours. Our lifetimes are defined in such an easy way, because the amount of calculation time is to high for a more complex definition. The histogram of the lifetimes shows a straight line in a logarithmic plot, that means it is possible to define something like a *decay time*. This decay time is the slope of the curve.

3. Results

The kink in the distribution of fractal dimensions is slightly moving to larger values (Figure 3) towards the minimum, the dispersion of the results is relatively small. This means that during solar minimum the point, where circular shaped granules change to complex structured ones is shifted upwards.

The mean perimeters (Figure 4) and mean areas (Figure 5) show both the same behaviour. Both are increasing slightly towards the solar minimum. An interesting fact is the small dispersion of the values during low solar activity.

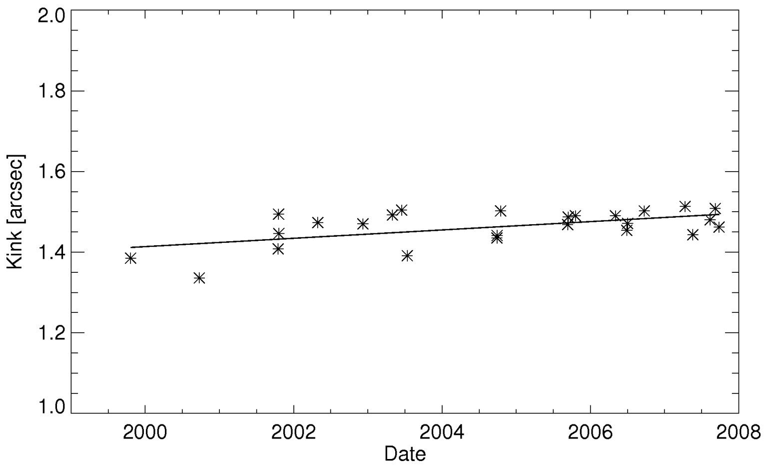

Figure 3: Fractal dimension – The position of the kink in the area-perimeter relation indicates the size of granules becoming more complex, this size seems to increase slightly with decreasing solar activity.

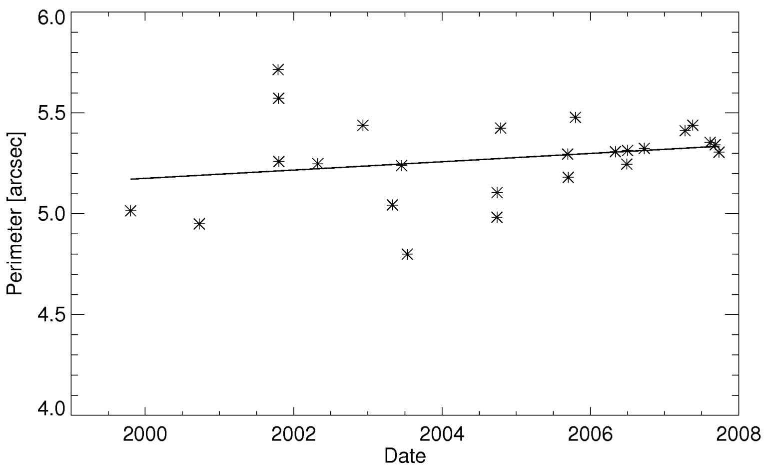

Figure 4: Mean perimeters of the granules show a large scatter which decreases towards solar minimum, the interpolated curve has a slightly positive slope.

Areas of granules and cells (Figure 6) show an opposite trend, areas of the granules become larger whereas cell sizes, obtained with the watershed method, decrease, also here the scatter becomes smaller.

The mean distances obtained form the triangulation method (Figure 7) are the only parameter that keeps constant all the time, in addition this value has only a very small dispersion.

Decay times (Figure 8) show a large scatter. The interpolation through the values shows a strong increase but this result is very uncertain.

We can summarize the results as follows: the kink in the fractal dimension, the granule areas, the perimeters, and the decay time are increasing with decreasing solar activity. The cell sizes become smaller towards the solar minimum and the distances between the granule centres are constant.

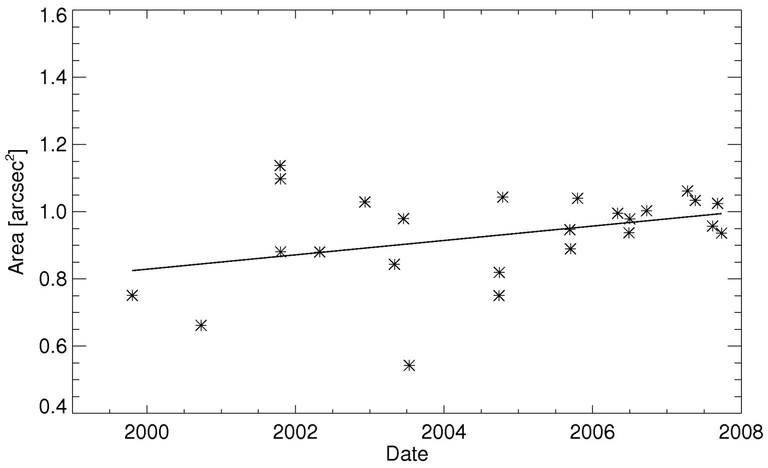

Figure 5: Mean granule areas obtained from the selection according to Roudier and Muller (1986) show the same behaviour as the perimeters in Figure 4.

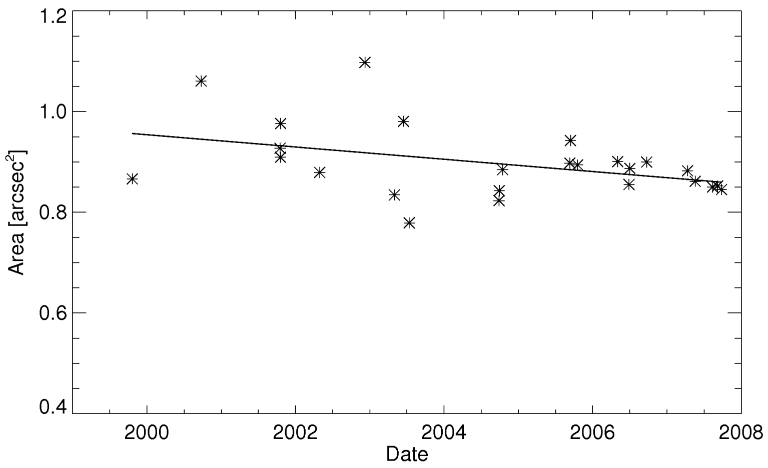

Figure 6: Cell areas show a strong decrease after the solar maximum but also here the data points less scattered during low activity times.

4. Discussion

At first glance there seems to be a discrepancy in the results: areas and perimeters are increasing but the distances keep constant. – This is in fact possible when the granule to inter-granule ratio changes. This can be checked easily just by counting granular pixels and this ratio really increases but with a very broad distribution from 42% to 53% granule fraction. Maybe for this purpose another much more sophisticated granule selection method should be used like the one presented in Bovelet and Wiehr (2007), but this method needs manual interaction, which is too time consuming for such an amount of data. An change in the spatial domain, i.e. in the size of the granules, was not confirmed by Muller *et al.* (2007).

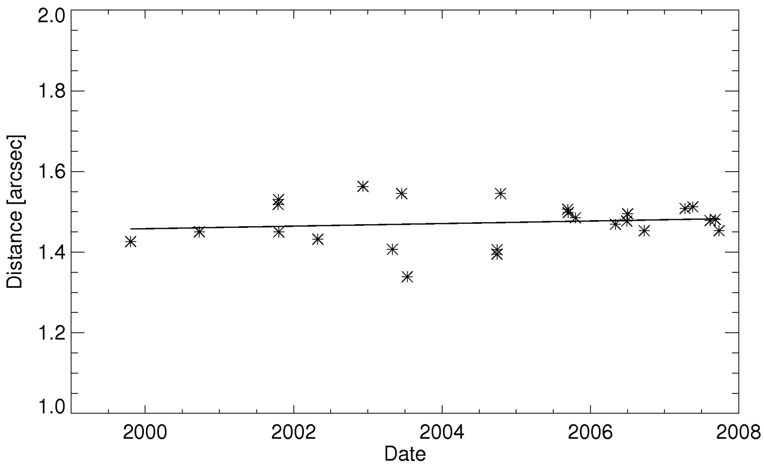

Figure 7: The mean granular distance from the triangulation method has only a small dispersion and is the only parameter, which keeps nearly constant over the time.

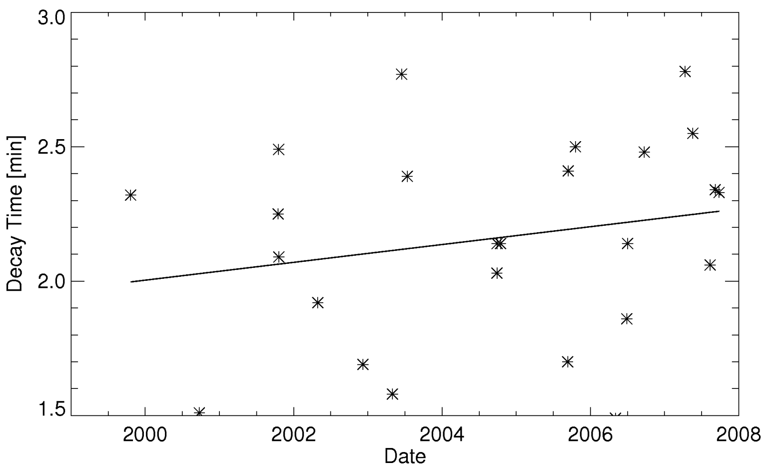

Figure 8: The decay times show a remarkable increase towards the solar minimum, but the scatter is so large that this result is very uncertain.

The value of the kink is a measure for the size of granules that change from circular shaped to structured granules. The increase of this value can be interpreted in the following way: towards solar minimum the circular shape of granules is not so strongly disturbed as during the maximum. This result is not in contradiction with the increased areas and perimeters, if both are shifted to higher values, the kink also moves.

When considering the way in which the cell sizes have been determined with the watershed algorithm it is evident that the granules are more structured and the granules should also be smaller. But what we don't see is the number of granules larger or smaller than the kink. If there are more larger very structured granules the mean cell size can decrease, because for each local maximum one cell is generated. Circular granules normally have one local maximum, the big structured ones, like exploding granules, can have 2 or more local maxima. In this case the cell sizes are in agreement with the results above.

The lifetimes show a very large dispersion around the value of 2 minutes, here the problem seems to be the definition of the lifetime, which is in this case more or less a fragmentation time, because a granule end is defined by a fragmenting or vanishing and the birth is defined by emerging or by a remnant of a fragmenting process. The values for the decay times therefore become very small (between 1.5 and 3 minutes), granular lifetimes should be about 6 minutes, which was found by Hirzberger *et al.* (1999a) in a very thorough processing. According to Hirzberger *et al.* (1999b) granule lifetimes should be higher in regions with lower G-band brightness where the activity is lower, even though our result for the decay times is very uncertain, the result is in agreement with this work.

There existed also the idea of weighting the results by the size of the data set but it is not clear how to set correct weights, there are differences between the number of images by a factor of 10, but there are long time series available especially for the years, where the values are scattered most (see Table I).

5. Future Work

The new solar cycle 24 has just begun with some high latitude spots. In the next 3 years the solar activity will increase significantly and this gives us the chance to do a lot of work in this field. By using another wavelength like the blue continuum (432 nm) the calculations can be made more accurate and in addition other parameters like the autocorrelation time, which is strongly disturbed by the bright points, can be calculated.

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