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Solar Cycle Phase Dependence of Supergranular Fractal Dimension

U. Paniveni[1,2,*], V. Krishan[2], J. Singh[2] & R. Srikanth[3,4]
[1]*NIE Institute of Technology, Mysore, India.*
[2]*Indian Institute of Astrophysics, Bangalore, India.*
[3]*Poornaprajna Institute of Research, 4 Sadashivnagar, Bangalore, India.*
[4]*Optics Group, Raman Research Institute, Bangalore, India.*
**e-mail: paniveni.udayashankar@gmail.com*

Abstract. We study the complexity of supergranular cells using the intensity patterns obtained from the Kodaikanal Solar Observatory during the 23rd solar cycle. Our data consists of visually identified supergranular cells, from which a fractal dimension D for supergranulation is obtained according to the relation $P \propto A^{D/2}$, where A is the area and P is the perimeter of the supergranular cells. We find a difference in the fractal dimension between active and quiet region cells in the ascending phase, during the peak and in the descending phase which is conjectured to be due to the magnetic activity level.

Key words. Solar cycle—supergranulation—fractal dimension.

1. Introduction

Heat flux transport is chiefly by convection rather than by photon diffusion in the convection zone of all cool stars such as the Sun. The convective motions on the Sun are characterized by two prominent scales: the granulation with a typical size of 1000 km and the supergranulation with a typical size of 30,000 km. The supergranules are regions of horizontal outflow along the surface, diverging from the cell centre and subsiding flow at the cell borders.

The approximate lifespan of a supergranular cell is 24 hours. Broadly speaking supergranules are characterized by the three parameters namely length L, lifetime T and horizontal flow velocity $v_{\rm h}$. The interrelationships amongst these parameters can shed light on the underlying convective processes.

Recently we showed that the velocity spectrum of the supergranular field very closely agrees with Kolmogorov's spectrum $v_{\rm h} = \epsilon^{1/3}L^{1/3}$ (Krishan *et al*. 2002) and $v_{\rm h} = \epsilon^{1/2}T^{1/2}$ (Paniveni *et al*. 2004) where ϵ is the energy injection rate. We have also suggested a possible turbulent origin of supergranulation based on a fractal analysis (Paniveni *et al*. 2005).

We have analysed intensitygrams obtained during the 23rd solar cycle at the Solar Observatory, Kodaikanal.

Intensitygram data have been obtained with a resolution of 2 arcsec, which is twice the granular scale. Fractal dimension attributed to a feature must be qualified by the resolution at which it is derived.

Well-accentuated cells of the intensity data lying between 15° and 60° angular distance from the disc centre were selected. This choice of the region discounts error due to projection effects.

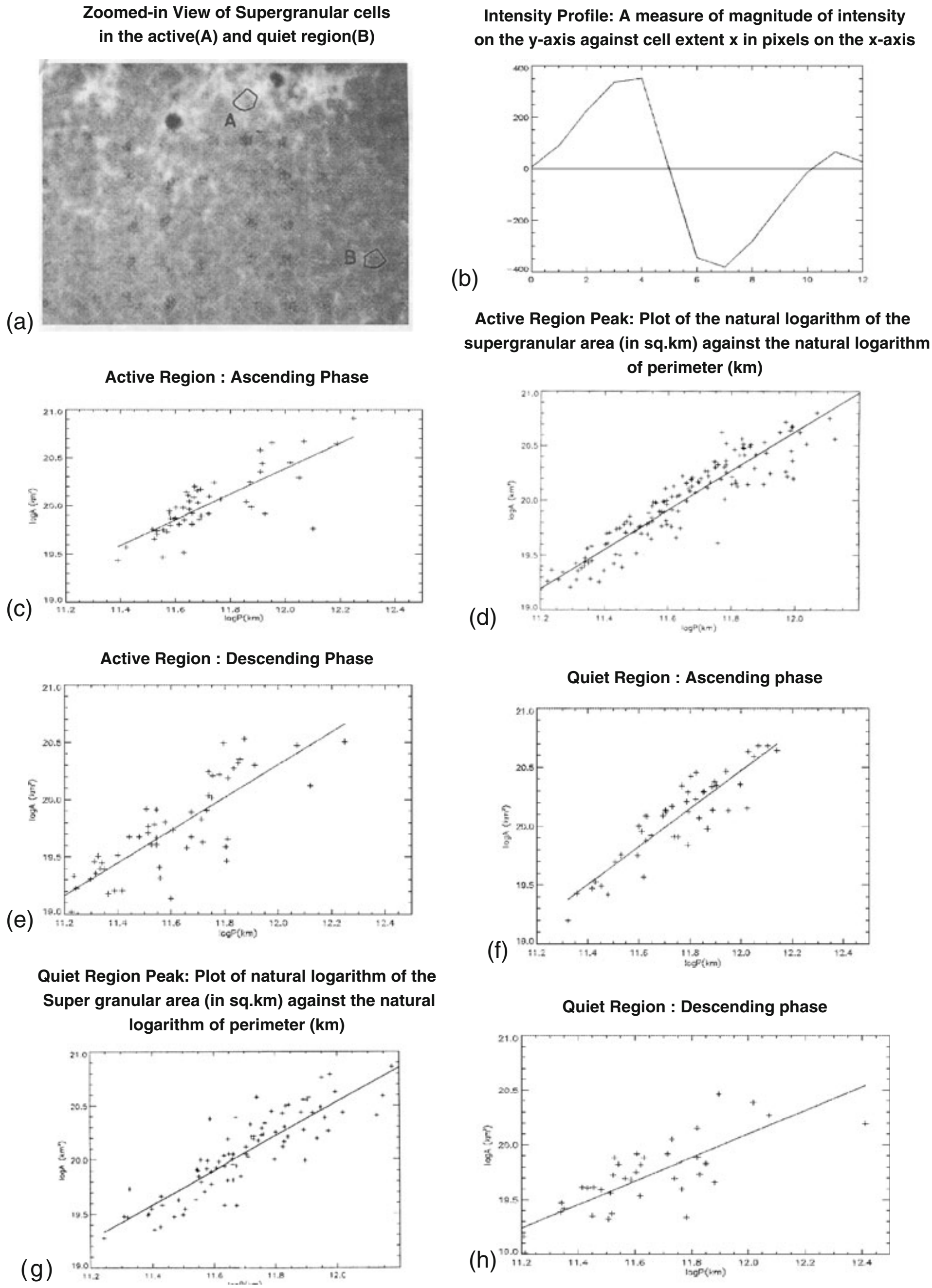

Figure 1. Outline, profile and area-perimeter data for active and quiet supergranular cells.

Depending on the region in which it is found, it is called 'quiescent' or 'active' (Fig. 1a). Regions that were not unequivocally quiescent or active were avoided for simplicity.

2. Data processing and results

The area and perimeter data were obtained by obtaining profile scans (Fig. 1b), details of which can be found in our earlier paper (Paniveni *et al.* 2005). The main results pertaining to fractal dimension is derived from Fig. 1(c, d, e, f, g, h). The linear relation in Fig. 1(c, d, e, f, g, h) suggests that supergranules are self-similar and may be regarded as fractal objects. Since $P \propto A^{D/2}$, we may expect D to be an important parameter characterizing the process which produces the solar supergranulation.

The $\log A$ *versus* $\log P$ relation is linear as shown in Fig. 1(c, d, e) for the active region at the ascending, peak and descending phases, respectively. Correlation coefficients of 0.8, 0.94 and 0.87 indicate a strong correlation in each case. Fractal dimension calculated as 2/slope are found to be $D = 1.325 \pm 0.282$, 1.12 ± 0.07, 1.431 ± 0.212, respectively.

The $\log A$ *versus* $\log P$ relation is linear as shown in Fig. 1(f, g, h) for the quiescent region at the ascending peak and descending phases respectively. Correlation coefficients of 0.9, 0.88 and 0.78 indicate a strong correlation in each case. Fractal dimension calculated as 2/slope are found to be $D = 1.616 \pm 0.221$, 1.25 ± 0.14, 1.075 ± 0.284.

3. Conclusions

The spectral distribution of the temperature, a passive scalar, is related to the spectral distribution of kinetic energy. It can be easily shown that the Kolmogorov energy spectrum, $K^{-5/3}$, both in two and three dimensional turbulence leads to a temperature spectrum of $K^{-5/3}$. Thus the temperature variance $\langle \theta^2 \rangle$ varies as $r^{2/3}$ as a function of the distance r (Tennekes & Lumley 1970). According to Mandelbrot (1975), an isosurface has a fractal dimension given by D_I=(Euclidean dimension)−1/2(exponent of the variance). Thus $D_T = 2 - (1/2 \times 2/3) = 5/3 = 1.66$ for an isotherm. The pressure variance $\langle P^2 \rangle$, on the other hand, is proportional to the square of the velocity variance, i.e., $\langle P^2 \rangle \propto r^{4/3}$ (Batchelor 1953). The fractal dimension of an isobar is therefore found to be $D_P = 2 - (1/2 \times 4/3) = 1.33$. Our data furnishes evidence that the fractal nature of the supergranular network is close to being isobaric than isothermal.

It is interesting that Roudier & Muller (1986) obtained a similar dimension for smaller granules. Unlike in granules, our plots show that a single linear fit is suitable for the entire observed range of supergranules. The self-similarity exhibited by a large range of scales of convection lends support to the turbulent convection based on horizontal flow velocity, lifetime and length scale data for supergranulation.

We have noted a theoretical or observational support for a relationship between supergranular scale size and the activity level (Singh & Bappu 1981; Meunier *et al.* 2007a). Nevertheless the variation of cell size with its magnetic environment remains controversial. Part of this state of affairs probably stems from lack of a consistent definition of activity level in that they do not distinguish between intra-cellular activity, network activity (as indicated by Meunier *et al*. 2007b) and the magnetic sensitivity of the data. We can hope that an extension of theoretical models that can account for the relationship between the scale and absolute field could also shed light on how magnetic fields may influence fractal dimension.

It is known that strong magnetic fields have an inhibiting effect on large scale flows, but a causal connection linking restricted velocity flows in the presence of magnetic fields to smaller fractal dimension is not obvious.

Our data shows a difference in the solar cycle phase dependence of fractal dimension, for active and quiescent regions. Whereas the active regions register a dip at the peak, quiescent regions fall monotonically through the cycle. A simplistic conclusion would be that for active regions, D is mainly a function of activity level alone, whereas for quiescent regions, there appears to be a 'memory' effect, namely an explicit dependence on phase.

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