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Theory of Supergranulation

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Abstract

Solar convection through supergranulation is examined through its various physical phenomena. Interrelationships amongst the parameters characterizing supergranular cells namely size, horizontal flow field, lifetime and physical dimensions of the cells and the fractal dimension deduced from the size data can reveal a wealth of information regarding its chaotic and turbulent aspects.
The findings are supportive of Kolmogorov's theory of turbulence.
Kodaikanal and SoHO data are used to study these parameters in the Solar maximum and Solar minimum phases respectively and the analysis mode is visual inspection and manual processing.

1 Introduction

Convection is the chief mode of transport in the outer layers of all cool stars such as the Sun (Noyes,1982). Convection zone of thickness 30% of the Solar radius lies in the sub-photospheric layers of the Sun. Here the opacity is so large that heat flux transport is mainly by convection rather than by photon diffusion. Convection is revealed on four scales. On the scale of 1-2 arcsec, it is granulation and on the scale of 8-10 arcsec, it is Mesogranulation. The next hierarchial scale of convection, Supergranules are in the range of 30-40 arcsec. The largest reported manifestation of convection in the Sun are 'Giant Cells' or 'Giant Granules, on a typical length scale of about 10^8 m. The lifetime of a granule is about 8 min, mesogranulation about 3 hours, supegranulation about 24 hours and giant cells about 1 month

Supergranules manifest regions of horizontal flow diverging from the cell centre with a typical speed (0.3-0.4) km/s and subsiding flows at thecell borders with a typical speed of about (0.1-0.2) km/s. (Leighton et al. 1962) By virtue of geometric projection, such outflowing regions showvelocity of approach on the side of the cell close to the centre and velocity of recession close to the limb. At the centre there is hardly any Doppler shift and hence it is almost uniformly grey (Fig (A)).

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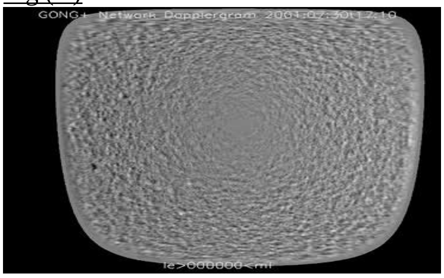
Fig (A)



Supergranulation is a physical pattern of the Sun with a typical horizontal scale of approximately 30000 km. It is a dynamical feature of turbulent magneto hydrodynamic convection.

Supergranulation was discovered more than 50 years ago. However explaining why and how it originates still represents one of the main challenges of modern solar physics. Observational constraints, conceptual difficulties and numerical limitations have prevented a detailed understanding of supergranular phenomenon so far.

Supergranulation undergoes oscillations and supports waves with periods 6-9 days. The waves are predominantly prograde which explains the apparent superrotation of the pattern. The rotation of the plasma through which the pattern propagates is consistent with the motion of the magnetic network

With the 21st century supercomputing resources and availability of unprecedented high resolution observation of the Sun, more details of the Sun can be unearthed.

Source of data

I have used 33 hour data of full disc Dopplergram obtained on 28th and 29th June 1996 by the Michelson Doppler interferometer on board the solar and Heliospheric observatory (SOHO) (Scherrer et al. 1995).
(Solar Minimum phase)
Also I have used Ca II K intensity data from Kodaikanal Solar Observatory obtained in 2001
(Solar Maximum phase)

Data Analysis

Both the Dopplergram data and the 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. (Krishan et al., 2002, Paniveni et al.,2004)

Further data is averaged over an interval of 10 m, twice the 5 m period.
P-mode vibration is reduced after time averaging.

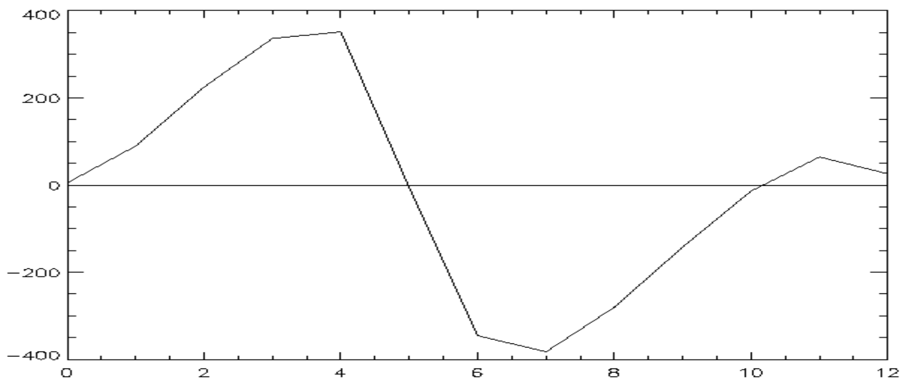
Our analysis of Dopplergrams rests on the implicit belief that time averaging removes noise significantly.

Well accentuated cells of the Doppler and Intensity data lying between 15 degree and 60 degree angular distance from the disc centre were selected. This choice of the region discounts error due to projection effects. SoHO data is used for Area-Perimeter relationship analysis and Kodaikanal data is used for Supergranular Circularity measurement.

The profile of a visually identified cell was scanned as follows:
I chose a fiducial y-direction on the cell and performed intensity profile scans for Intensitygrams and the velocity profile scan for Dopplergrams along the x-direction for all pixel positions on the y-axis. In each scan, the cell extent is taken to be marked by two juxtaposed ‘crests’ separated by a trough expected in the Dopplergram or in the Intensitygrams (Fig(1)). (Paniveni et al., 2005 ; Paniveni et al., 2010)
This set of data points was used to determine the area and perimeter of a given cell and of the spectrum for all selected supergranules.

Circularity of each of the cells is deduced by using a software programme written in IDL.

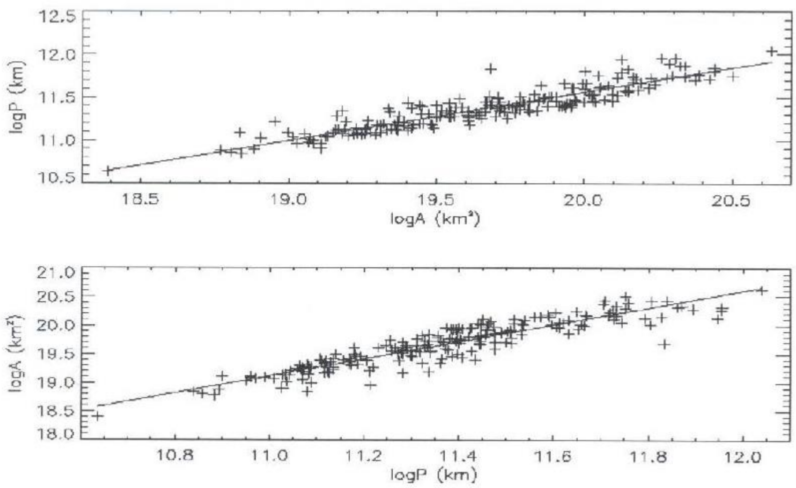
Fig(1)



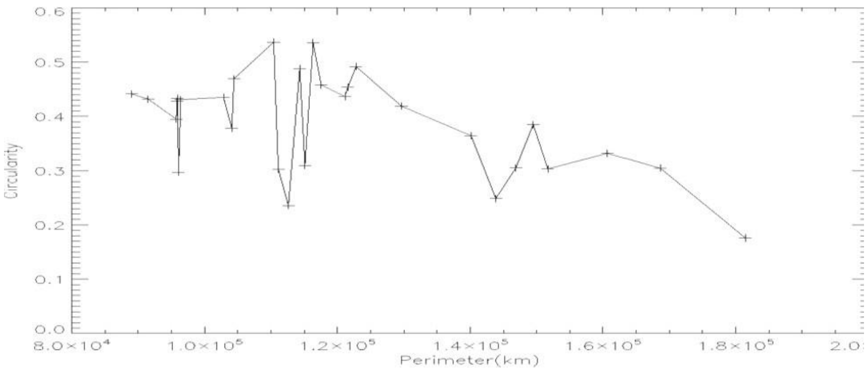
Results

logP vs logA ~~versus~~ plots and Perimeter vs circularity are shown in Fig (2) and Fig (3) as under:
Calculation of Fractal dimension using the relation Pα $A^{D/2}$ is ~~calculated~~ found to beabout 1.25 which is closer to 1.33 and projects isobaric nature of supergranular flow. Perimeter vs Circularity graph which shows that the mid -range cells are more circular.

Fig (2)



Fig(3)



Discussion:

Kolmogorov's theory is an asymptotic theory. It is known to work well in the limit of very high Reynold's number. It assumes that energy cascade is one way and is from large to small eddies. Experiments have shown that energy is also transferred from smaller to larger scales, a process called backscatter.
It deals with the energy spectrum of turbulence. It shows the distribution of energy amongst turbulent vortices as a function of vortex size. The wave number 'k' of vortex of spatial dimension 'L' is given by $k=2\pi/L$.
The spectral form of Navier-Stokes equations indicates that energy can be transferred from two wave numbers k_1, k_2 to a wave number k_3 only if $k_3 = k_1 + k_2$ according to the selection rule. If $k_1 = k_2$, then $k_3 = 2 k_1$

Kolmogorov envisioned a process in which mixing occurs from k_{min} to k_{max}. In the inertial range viscous dissipation is not important.
If E is the energy density per unit wave number and it depends only on 'k' and energy injection rate 'ε'.
$k= 1/L$ and $\varepsilon=L^2/T^3$ and $E=L^3/ T^2$
If $E(k, \varepsilon) = C k^\alpha \varepsilon^\beta$ for constant 'C'.
Dimensional compatibility requires that $L^3 = L^{-\alpha} L^{2\beta}$
$-\alpha +2\beta = 3$
$T^{-2} = T^{-3\beta}$ and hence $-3\beta= -2$ or $\beta = 2/3$
Therefore $\alpha = 4/3 – 3 = -5/3$
Kolmogorov energy spectrum can be expressed mathematically as
$\mathbf{E(k, \varepsilon) = c\, k^{-5/3} \varepsilon^{2/3}}$

Conclusion

Interrelationships of the parameters of supergranulation have been studied in a series of analyses. Isobaric nature of supergranulation is established in this analysis, thus paving way for a chaotic phenomenon.
Supergranulation is believed to be governed by a turbulent convection conceding the Kolmogorov's theory of turbulence. Much needs to understood about this phenomenon.

Numerical modelling is the best way to study the interior. But as the convection zone is highly turbulent and stratified, numerical modelling has proved to be difficult and dynamics remain poorly understood.

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