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Relationship between horizontal flow velocity and cell lifetime for supergranulation from *SOHO* Dopplergrams

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ABSTRACT

A study of 50 supergranular cells obtained from *Solar and Heliospheric Observatory* (*SOHO*) Dopplergrams was undertaken in order to investigate the relationship between the lifetime (T) and the horizontal flow velocity (v_{h}) of the cells. For this sample, we find that the two parameters are correlated with a relation $v_{\mathrm{h}} \propto T^{1/2}$ and T is identified by the eddy turnover time. This is in agreement with the turbulent convective model of the solar atmosphere, where the velocity spectrum of the supergranular field, given by the relation $v_{\mathrm{h}} \propto L^{1/3}$, can be identified with the Kolmogorov spectrum for the eddy size L.

Key words: turbulence – Sun: granulation.

1 INTRODUCTION

Convection is the chief mode of transport of heat in the outer envelopes of cool stars such as the Sun (Noyes 1982). The convection zone that lies in the subphotospheric layers of the Sun has a thickness of approximately 30 per cent of the solar radius. Here the opacity is so large that energy is carried by turbulent motions rather than by photon diffusion. 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. Such outflowing regions always show the velocity of approach to the observer on the side close to the centre of the disc and the velocity of recession on the side towards the limb. Near the centre of the disc, where the horizontal outflows are almost transverse to the line of sight, there is less Dopplershift and the image is almost uniformly grey. These high photospheric large convective eddies sweep up any shreds of photospheric magnetic fields in their path from the declining active regions into the boundaries of the cell, where they produce excess heating, resulting in the chromospheric network. The approximate lifespan of a supergranular cell is 24 h. Broadly speaking supergranules are characterized by three parameters namely length L, lifetime T and horizontal flow velocity v_{h}. The interrelationships amongst these parameters can shed light on the underlying convective processes. The lifetime of network cells was found to be larger for active-region cells as compared with that of quiet-region cells (Raju, Srikanth & Singh 1998). Diffusion-like dispersion of the magnetic flux is the dominant factor in the large-scale evolution of the network. Convective motion and magnetic inhibition of motion are both stronger in active regions, thereby leading to similar speeds in all regimes (Srikanth, Singh & Raju 1999). The lifetime of a supergranular cell is found to depend on the size of the cell and is larger for bigger cells. Cells of a given size associated with remnant magnetic field regions live longer than those in the field-free regions (Singh et al. 1994). A positive correlation between horizontal flow velocity and cell size of a supergranular cell has been uncovered recently by Krishan et al. (2002). The corresponding dependence of the lifetime of the supergranular cell on its horizontal flow velocity is expected to be $v_{\mathrm{h}} \propto T^{1/2}$, where the eddy turnover time, i.e. the crossing time for plasma from centre to edge, can be estimated from the relation $T = L/v_{\mathrm{h}}$ with L as the distance from the centre to the edge of the cell and v_{h} is the peak horizontal flow velocity of the cell. In this paper we report on this possible interrelationship between horizontal flow velocity and cell lifetime for supergranules.

2 DATA ANALYSIS

2.1 Source of data

We analysed 33-h data of full disc Dopplergrams obtained on 1996 June 28 and 29 by the Michelson Doppler Interferometer (MDI) on board the *Solar and Heliospheric Observatory* (*SOHO*, Scherrer et al. 1995).

2.2 Data processing

The *SOHO* full disc Dopplergram data was obtained with a resolution of 2 arcsec, which is twice the granular scale. Furthermore, the Dopplergrams are time averaged over intervals of 10 min, which is approximately twice the 5-min period of oscillations. Thus the signal due to granular velocity is averaged out. Similarly the contributions due to p-mode vibrations are reduced after time averaging.

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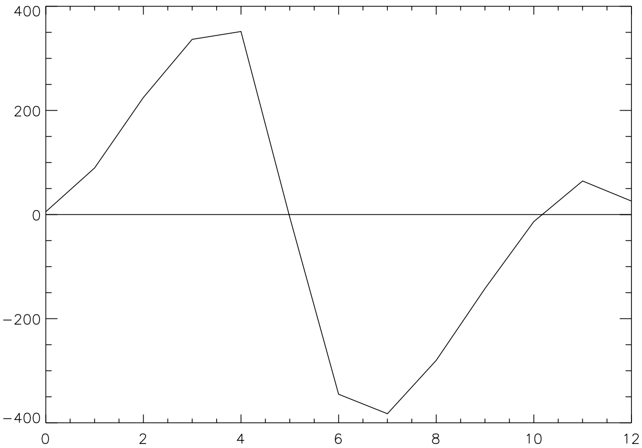

Figure 1. Profile of the line-of-sight velocity component v_L (in units of m s^{-1}) on the *y*-axis against cell extent *x* (in units of 2 arcsec) on the *x*-axis.

Our analysis rests on the implicit belief that time averaging significantly removes noise. Noise is reduced in our data considerably with 10-min integration time, as judged from visual inspection and also as seen in a typical supergranular velocity profile for our data (Fig. 1). After the averaging, the supergranular network is brought out with reasonable clarity. This procedure usually yielded six images per hour of the data. Corrections due to solar rotation are applied to the Dopplershifts. 50 well-accentuated cells lying between 15° and 60° angular distance from the disc centre were selected. Restricting to the above-mentioned angular distance limits helps us discount weak supergranular flows and foreshortening effects.

2.3 Supergranular cell speed

The line-of-sight velocities in the dark/bright region of the cells are directly read off from the velocity scan. Among them the first three greatest velocity read-outs and the last three least velocity read-outs were selected. The maximum cell velocity is then determined as the average of the former three values minus the average of the latter three. This furnishes a simple way to assign a peak horizontal flow velocity $v_{\rm h}$ to a given cell that is independent of large-scale velocity gradients. To see this let us write $v_{\rm max} = |v_{\rm h}| + v_{\oplus}$ where $v_{\oplus}$ represents contributions due to large-scale gradients in the velocity field and $v_{\rm min} = -\,|v_{\rm h}| + v_{\oplus}$. Then half the difference of $v_{\rm max}$ and $v_{\rm min}$ is the required peak horizontal velocity $v_{\rm h}$. Three pairs of values were chosen to add robustness. Now, it is a fact that even a randomly noisy velocity field can, by our method of choice of three largest velocities, be biased to yield some spurious relations (e.g. larger cells showing larger velocity). Hence it is of considerable importance to be certain that the data are not noisy at the level of interest. The ten-minute time-averaging removes noise to a level sufficient for our purpose. This was clear from a visual inspection of the images. More specifically, the selected three peak positive velocity points and the three peak negative points are not spiky and fit in smoothly with the surrounding flow pattern and hence the probability is very high that the chosen peaks are with part of the velocity profile and not noise. This is depicted for a typical cell profile in Fig. 1.

Dopplergrams give us the line-of-sight velocity component. Geometrically it has a contribution from the local horizontal flow field $v_{\rm h}$ and vertical flow field $v_{\rm v}$. Normally, the vertical component can be ignored because the convective upwelling, concentrated towards the cell centre, and the downflows, along the periphery of the cell, are typically much smaller. However, regions with a considerable vertical component of velocity are not improbable. For example, the upflow regions can be as broad as 10 arcsec (Küveler 1983). More importantly, it follows from basic trignometric arguments that our method of velocity selection will tend to pick up the three largest positive values from approaching flows with a considerable upflow component, and the (magnitudinally) largest negative values from receding flows with a considerable downward component. Therefore, in order to account for this residual $v_{\rm v}$ contribution (where we treat upflows and downflows symmetrically for simplicity), we need to make an assumption concerning the relation connecting $v_{\rm h}$ and $v_{\rm v}$. The velocity derived from our analysis is based on this assumption. In the reported literature, $v_{\rm h}$ is known to be larger than $v_{\rm v}$. This is also supported by mass conservation law (Krishan 1999; Krishan et al. 2002). Direct inspection of the disc centre yields vertical velocities of approximately 200 m s^{-1}. For $v_{\rm h} = 539.15$ m s^{-1}, which we obtain as mean value, this implies a value closer to $r \equiv v_{\rm v}/v_{\rm h} = 0.4$. Hence this value of *r* is adopted for the present analysis.

2.4 Supergranular cell Lifetime

The 33-h data are spread over 198 frames with a 10-min interval between the consecutive frames. Only those cells that appear and disappear within the chosen period of 33 h are considered. This excludes cells already present in the first frame and those still present in the last frame. Thus the selected cells were born a few frames after the first. A particular supergranular cell thus identified is tracked down the successive frames until it disappears completely in a particular frame. Lifetime is identified to be the time interval between its first appearance and final disappearance.

3 RESULTS

A large dispersion in the supergranular lifetime and horizontal velocity is noted. The main results pertaining to the maximum, the minimum, the mean and the standard deviation for the cell lifetime *T*, the horizontal flow velocity $v_{\rm h}$ and the cell size *L* are summarized in Table 1.

In previous studies cell lifetimes were derived by cross-correlation techniques (Srikanth, Raju & Singh 1999). The analysis was based on diffusion coefficients of the network magnetic elements and was identified as a 'diffusion lifetime'. Estimation of the lifetime by a visual inspection method rests on the crossing time for plasma from the centre to the edge of the cell (Krishan 1999). Hence visual inspection is expected to lead to the eddy turnover time given by $T = L/v_{\rm h}$. Visual inspection is a fairly foolproof method, though laborious. The sample is quite small, but is characteristic for different epochs and regions.

Fig. 2 presents a plot of peak horizontal flow velocity with $r = 0.4$ and cell lifetime. A power-law of the form

$$v_{\rm h} = CT^{\alpha} \tag{1}$$

Table 1. Maximum, minimum, mean and standard deviation for the cell lifetime (*T*), the cell peak horizontal flow velocity ($v_{\rm h}$) and the cell size (*L*).

	Max	Min	Mean	Σ
T (h)	32.00	16.00	22.00	3.0
$v_{\rm h}$ (m s^{-1})	661.06	402.33	539.15	1.8
L (Mm)	42.79	17.63	27.42	5.75

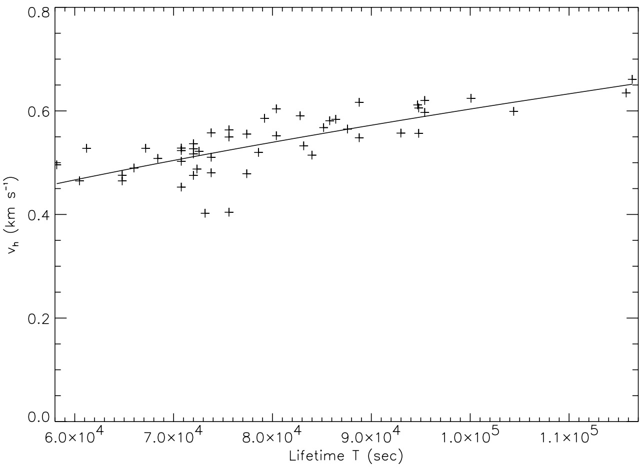

Figure 2. Plot of the peak horizontal velocity v_h of the supergranular cell against the cell lifetime T. The measured values are represented by the plus signs. The line represents the least-squares fit to equation (1).

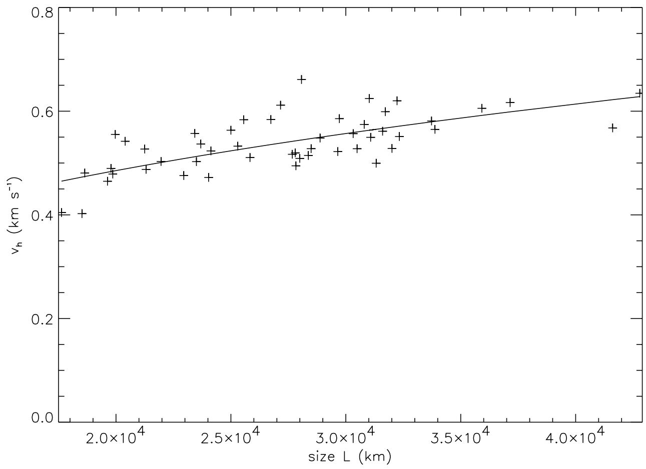

Figure 3. Plot of peak horizontal velocity v_h against cell size L. The measured values are represented by plus signs. The line represents the least-squares fit equation $v_h = \epsilon^{1/3} L^{1/3}$.

was fitted to the data using the least-squares method. We find $C \sim 0.001$ and $\alpha = 0.51$. The intercept gives the value of $\epsilon \approx 3.6 \times 10^{-6}$ km^2 s^{-3}. Fig. 2 clearly shows that the two parameters are fairly well correlated. In particular, the correlation coefficient between v_h and $T^{1/2}$ is approximately 0.76.

4 DISCUSSION AND CONCLUSIONS

In an earlier study (Krishan 1991), it was suggested that granulation and supergranulation are the result of energy cascading processes in a turbulent medium. Recently, we showed that the velocity spectrum of the supergranular field very closely agrees with Kolmogorov's spectrum $v_h = \epsilon^{1/3} L^{1/3}$ (Krishan et al. 2002) where ϵ is the energy injection rate. Defining the eddy turnover time to be the lifetime of the cell, we can write $T = L/v_h$. Combining with the Kolmogorov spectrum $v_h = \epsilon^{1/3} L^{1/3}$, we find

$$v_h = \epsilon^{1/2} T^{1/2}. \tag{2}$$

Comparing (1) and (2) we see that $C = \epsilon^{1/2}$ and hence $\epsilon = 10^{-6}$ km^2 s^{-3}, which is very close to the value of ϵ obtained earlier by us (Krishan et al. 2002) from the velocity v_h and size L relationship with different data. Using the data of peak horizontal flow velocity of 50 supergranular cells and their sizes, we have plotted the data of v_h against L as shown in Fig. 3. Its intercept gives the value of $\epsilon \approx 5.26 \times 10^{-6}$ km^2 s^{-3} and a slope of 0.33. A correlation coefficient for v_h and $L^{1/3}$ of 0.68 is obtained. Thus we conclude that the supergranular velocity field is well accounted for by the Kolmogorov spectrum $v_h = \epsilon^{1/3} L^{1/3}$ with eddy turnover time realized from $v_h = \epsilon^{1/2} T^{1/2}$. A comparison of the theoretical energy spectrum of granulation ($\propto K^{-5/3}$), mesogranulation ($\propto K^{-1}$) and supergranulation ($\propto K^{-5/3}$) (Krishan 1991, 1996) with the observed energy spectrum of granulation ($\propto K^{-5/3}$), mesogranulation ($\propto K^{-0.7}$) and supergranulation ($\propto K^{-5/3}$) (Malherbe et al. 1987; Zahn 1987; Keil et al. 1994) appears to indicate the phenomenon of the inverse cascade of energy operating in the solar convective turbulence.

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REFERENCES

Keil S., Kuhn J., Lin H., Reardon K., 1994, in Rabin D.M., Jefferies J.T., Lindsey C., eds, Proc. IAU Symp., Vol. 154, Infrared Solar Physics. Kluwer, Dordrecht, p. 251
Krishan V., 1991, MNRAS, 250, 50
Krishan V., 1996, Bull. Astron. Soc. India, 24, 285
Krishan V., 1999, Astrophysical Plasmas and Fluids. Kluwer, Boston
Krishan V., Paniveni U., Singh J., Srikanth R., 2002, MNRAS, 334, 230
Küveler G., 1983, Sol. Phys., 88, 13
Malherbe J.M., Mein P., Muller R., Roudier R., Coutard C., Hellier R., 1987, in Mouradian Z., Lemaire P., eds, Colloq. Themis, 5th European meeting on Solar and Stellar Physics. Obser. Paris Press, Paris, p. 53
Noyes R.W., 1982, The Sun, Our Star. Harvard Univ. Press, Harvard, Cambridge, MA
Raju K.P., Srikanth R., Singh J., 1998, Sol. Phys., 180, 47
Scherrer P.H. et al., 1995, Sol. Phys., 162, 129
Singh J., Nagabhushana B.S., Babu G.S.D., Wahab Uddin, 1994, Sol. Phys., 153, 157
Srikanth R., Singh J., Raju K.P., 1999, Sol. Phys., 187, 1
Srikanth R., Raju K.P., Singh J., 1999, Sol. Phys., 184, 267
Zahn J.P., 1987, in Schröter E.H., Schussler M., eds, Solar and Stellar Physics. Springer-Verlag, Berlin, p. 55

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