2002MNRAS.334..230K

Mon. Not. R. Astron. Soc. **334,** 230–232 (2002)

Relationship between horizontal flow velocity and cell size for supergranulation using *SOHO* Dopplergrams

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Accepted 2002 March 21. Received 2002 February 24; in original form 2001 May 22

ABSTRACT

A study of 90 supergranular cells obtained from *SOHO* Dopplergrams was undertaken in order to investigate a possible relation between the sizes and peak horizontal velocities of the cells. For the sample obtained, the two parameters are found to be correlated with a relation: horizontal velocity $\propto$(size)$^{1/3}$. This is in agreement with the Kolmogorov theory of turbulence as applied to large-scale solar convection.

Key words: turbulence – Sun: granulation.

1 INTRODUCTION

Observations of the Solar photosphere through high-resolution instruments have indicated that the Solar surface is granular and shows irregular polygonal brightness patterns surrounded by dark lanes. These cellular velocity patterns are a visible manifestation of the sub-photospheric convection currents which contribute substantially to the outward transport of energy from the deeper layers, thus maintaining the energy balance of the sun as a whole.

The convection zone of thickness equal to 30 per cent of the solar radius lies below the photosphere and is revealed by two surface network patterns. On the scale of 1000 km it is the granulation, with a typical lifetime of 8–10 min and on a scale of 30 000 km, it is supergranulation with a typical lifetime of 24 h. Supergranules are observed in the high photosphere as large convection eddies with horizontal diverging flows from the cell centre and subsiding flows at the cell borders. Horizontal currents associated with each supergranule are believed to sweep magnetic fields from the declining active regions into the boundaries of the cell where they produce excess heating resulting in the chromospheric network. A dependence of the network size on the magnetic activity has been suggested (Chandrashekar 1961). Similarly a dependence of the calcium network cell size on the solar cycle, with a smaller size at solar maxima, has been reported by Singh & Bappu (1981). Singh et al. (1994) have also reported a positive correlation between cell sizes and cell lifetimes.

The bright chromospheric network observed in Ca II K and Hα core filtergrams shows a dependence of autocorrelation size of the cells on the latitude. The size shows an approximate N–S symmetry with two minima at 20° N and 20° S (Raju, Srikanth & Singh 1998). Active cells close to the periphery of a plage are found to live longer than those in the quiescent regions. The confining properties of the magnetic field may be responsible for the longer life of active cells.

In this paper we report on the interrelationship, if any, between the supergranular size and the horizontal component of the convective flow field of the cell. This can shed light on how convection scales are related to the convective heat throughput and on the possible turbulent origin of the velocity field.

2 DATA ANALYSIS

2.1 Source of data

We analysed 20 h of full disc Dopplergrams obtained on 1996 June 28 by the Michelson–Doppler Interferometer (MDI) experiment on board the *Solar and Heliospheric Observatory* (*SOHO*) (Scherrer et al. 1995).

2.2 Data processing

The *SOHO* full disc Dopplergram data is of 2 arcsec resolution, which is twice the granular scale. Further, the Dopplergrams are time averaged over intervals of 10 min, which is about twice the granular lifetime. This minimizes the signal owing to the granular velocity field. Similarly, p-mode contributions are also very weak after the time averaging. Moreover, they are expected to be strongest at the disc center (Küveler 1983), a region we have excluded because of the poor supergranular horizontal component signal. The accentuation of the supergranular signal is also borne out by direct visual inspection. Before the 10-min averaging, the image is quite 'noisy' with no discernible supergranules. After the averaging, however, the supergranular network is brought out with fair clarity. This procedure yielded usually six images per hour of data.

Doppler shifts caused by the solar rotation were corrected for. Supergranular cells were identified in each of these averaged

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2002MNRAS.334..230K

images by a careful visual inspection. Not all of the dual bright–dark patterns characteristic of Dopplergrams are clearly delineated. Only cells with high-contrast borders were considered for the study. On this basis about 150 cells were chosen. Of these, 90 cells, which were in the range $15° < \theta < 60°$, were selected. Here θ is the angular distance of the cell from the disc centre. Cells below this range show weak supergranular flow signature. Those above the upper limit are beset with foreshortening effects that cannot be corrected for without some residual uncertainties.

2.3 Supergranular cell size

The profile of a visually identified cell was scanned as follows: we chose a fiducial y-direction on the cell and performed velocity profile scans along the x-direction for all the pixel positions on the y-axis. In each scan, the cell extent is taken as the sum of the base sizes of the juxtaposed 'crest' and 'trough' expected in the Dopplergrams. The sum of all these values at all y-levels multiplied by the pixel dimension gives the area of the cell. The square root of this is taken to represent the length-scale of the cell. The true size is obtained from the measured size by correcting for the projection effects.

2.4 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 highest 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 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.

Dopplergrams give us the line-of-sight velocity component. Geometrically it has a contribution from the local horizontal flow field $v_{\rm h}$ and the vertical flow field $v_{\rm v}$. Normally, the vertical component can be ignored because the convective upwelling is concentrated towards the cell centre. However, it turns out that the values of $v_{\rm h}$ were also derived close to the cell centre. A non-trivial contribution from $v_{\rm v}$ thus does not seem improbable, considering that the upflow regions can be as broad as 10 arcsec (Küveler 1983). To distinguish between these contributions, we need to make an assumption about the relation connecting $v_{\rm v}$ to $v_{\rm h}$. 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 the mass conservation law (Krishan 1999). Typically $v_{\rm h}$ lies in the range 0.3–0.5 km s^{-1} and $v_{\rm v}$ in the range 0.1–0.2 km s^{-1} (Foukal 1990). Then, assuming a uniform relation of the type $v_{\rm v} = r v_{\rm h}$, r is expected to lie in the range 0.2–0.7. A correlation check between the cell size and derived $v_{\rm h}$ gives the best fit for $r = 0.6$, with a correlation of 0.55. The correlation was found to fall systematically when r is decreased to $r = 0$, or increased. At $r = 0$, the correlation coefficient vanishes. For this reason, we have retained $r = 0.6$ as a uniform ratio throughout the solar surface.

3 RESULTS

A large dispersion in the supergranular sizes and the horizontal velocities is noted. The main results pertaining to the horizontal velocities $v_{\rm h}$ and the length-scales L of the supergranular cells are summarized in Table 1. The average cell size is larger than the earlier reported value of 23 Mm derived by visual inspection, though sizes obtained by autocorrelation can indeed be larger (Singh & Bappu 1981).

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

	Max	Min	mean	σ
L (Mm)	57.8	15.5	33.7	8.96
$v_{\rm h}$ (m/s)	757.4	285.5	491.1	74.1

This suggests a possible bias towards bigger cells in our study. Since only those cells with clearly delineated boundaries were chosen, and usually larger cells are more apparent to visual inspection, this could explain the possible bias. As an extreme case, our results must be taken to apply only to larger cells. However, we believe that it is unlikely that the same physical conditions do not apply also to smaller cells.

In previous studies, we derived cell size using the autocorrelation technique, which permits one to sample large areas. However, autocorrelation is not without its problems. For one, it represents an average, rather than realistic, size of cells in a region (Srikanth, Raju & Singh 1999). Moreover, it tends to overestimate the actual sizes (Singh & Bappu 1981).

Specifically in the case of Dopplergrams, although it is straightforward to estimate cell sizes via autocorrelation, there is no simple and clear procedure to estimate cell velocities in this way. Direct visual inspection is fairly foolproof if laborious. To make the data on sizes and velocities uniform, we decided to derive cell sizes also by visual inspection. Although the sample itself is small, it is quite characteristic for different regions on the quiet Sun, because the cells were chosen from different epochs and regions.

Fig. 1 presents a plot of cell horizontal velocity component with $r = 0.6$ against cell size. A power law of the form

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

was fitted to the data using the least-squares method. For $r = 0.6$, we find $f = 0.014 \pm 0.007$ and $\alpha = 0.34 \pm 0.046$. Fig. 1 clearly shows that the two parameters are well correlated. The correlation coefficient between $v_{\rm h}$ and L is about 0.55, which improves to about 0.6 when the functional dependence in equation (1) is taken into consideration.

4 DISCUSSION AND CONCLUSIONS

If we apply the Kolmogorov hypothesis for a turbulent medium to the solar convective motions, we expect that the supergranular horizontal velocity $v_{\rm h}$ depends on its size L as $v_{\rm h} = \epsilon^{1/3} L^{1/3}$, where ϵ is the energy injection rate. Comparison with equation (1) suggests the identification $f = \epsilon^{1/3}$. According to the turbulent convection theory $\epsilon = v^2/\tau$, where τ could be identified with the lifetime of a supergranular cell and v is a typical velocity. Thus $\epsilon = (0.5)^2/(24 \times 60 \times 60) = 2.89 \times 10^{-6}$ km^2 s^{-3}. From the results reported in the previous section and the curve fitting to equation (1), we find $f \approx 10^{-2}$. This implies $\epsilon \equiv f^3 = 10^{-6}$ km^2 s^{-3}.

It is interesting that both the ideas of the direct (Zahn 1987) and the inverse cascade (Krishan 1991) of energy in a turbulent medium predict Kolmogorov's law of $L^{1/3}$ for supergranulation.

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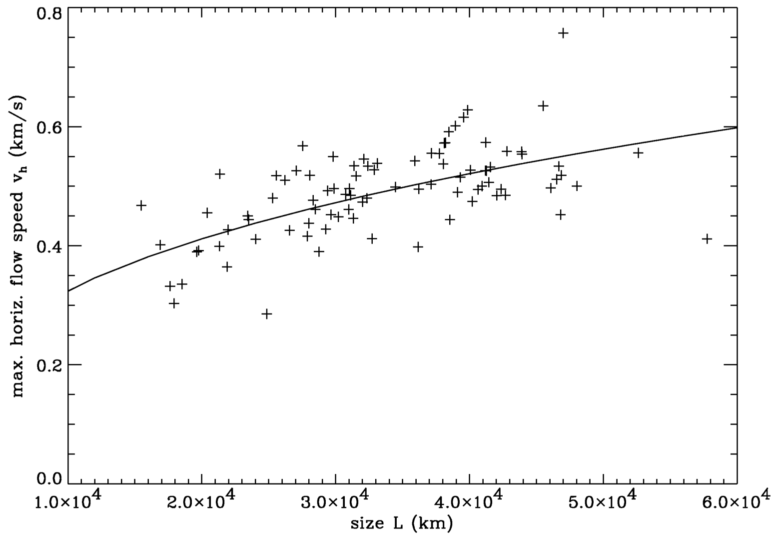

Figure 1. Plot of peak horizontal velocity v_h against cell size L. The measured values are represented by the plus signs. The line represents the least-squares fit to equation (1).

One may also recall that Kolmogorov's $K^{-5/3}$ law for granulation and $K^{-0.7}$ for mesogranulation have been inferred from observations (Malherbe et al. 1987; Zahn 1987; Keil et al. 1994). The hypothesis for inverse cascade predicts a K^{-1} spectrum for mesogranulation and $K^{-5/3}$ for granulation and supergranulation (Krishan 1991; 1996). Thus the observed entire spectrum for granulation, mesogranulation and supergranulation of $K^{-5/3}–K^{-0.7}–K^{-5/3}$ seems to favour the inverse cascade hypothesis.

ACKNOWLEDGMENTS

We thank Dr P. H. Scherrer and the *SOHO* consortium for providing us with the MDI/SOI data. We are grateful to the anonymous referee for comments that have helped make our presentation clearer. VK acknowledges receiving scholarship from FAPESP, Proc. No. 99/10529-0.

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