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Is solar mesogranulation a surface phenomenon?

S.R.O. Ploner[1,2], **S.K. Solanki**[1,2], **and A.S. Gadun**[3]

[1] Institute of Astronomy, ETH-Zentrum, 8092 Zürich, Switzerland
[2] Max-Planck-Institute of Aeronomy, 37191 Katlenburg-Lindau, Germany
[3] Main Astronomical Observatory of Ukrainian NAS, Goloseevo, 252650 Kiev-22, Ukraine

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Abstract. Convection is the main form of energy transport in the subsurface layers of the sun and other cool stars. The imprint of cellular convection can be directly observed on the solar surface, with a hierarchy of four size scales. The smallest observed convection cells, called granules, have typical horizontal sizes of 1,000–2,000 km and have been successfully reproduced by numerical simulations (Spruit 1997; Stein & Nordlund 1998). Cells at three larger scales are also detected (Leighton et al. 1962; November et al. 1981; Beck et al. 1998), but these have so far not been amenable to numerical modelling, so that their formation scenarios remain untested. Here we present a numerical simulation which resolves both the granular and the next larger, mesogranular, scale. The mesogranules have horizontal extents of 5,000–10,000 km. Our 2D simulation reproduces key properties of both granules and mesogranules. In addition, our simulation demonstrates that the observed mesogranulation is driven close to the solar surface and therefore rules out the text-book explanation of mesogranulation as cellular convection driven by superadiabaticity in the deeper layer where neutral helium ionizes. By proxy, this result also casts doubt on the traditional explanation of supergranulation, even larger convection cells with diameters of 20,000–30,000 km, as being driven by the yet deeper second ionization of helium.

Key words: convection – hydrodynamics – methods: numerical – Sun: granulation

1. Introduction

Convection plays a fundamental role in the transport of energy through the interior of the sun and most other stars. Solar convection is further known to underly the concentration and diffusion of large- and small-scale magnetic fields, as well as the generation of global solar oscillations and smaller-scale acoustic waves. The latter waves contribute to basal chromospheric heating (Schrijver 1987) and, according to recent modelling, are indirectly responsible for most of the radiation from the field-free chromosphere (Carlsson & Stein 1995). In addition, convective motions excite waves within magnetic concentrations and also push the magnetic field lines around, which leads to field-line braiding and magnetic reconnection (Innes et al. 1997). These processes have been proposed as the major sources of coronal heating (Narain & Ulmschneider 1996).

Since Herschel's time (Herschel 1801) high-resolution imaging of the solar surface has revealed a granular pattern consisting of isolated bright cells (*granules*) surrounded by dark connected lanes (*intergranular lanes*). The granules are about 1 Mm in diameter and have lifetimes of around 8 minutes. Granulation is the visible manifestation of convective instability in the layers below the solar surface. The bright granules consist of hot rising gas (overshooting into the convectively stable solar photosphere), the intergranular lanes of cool downflowing gas.

At present, three additional, larger scales of solar convection are known from observations. The smallest of these is the *mesogranulation* discovered by November et al. (1981) with typical cell sizes between 3 and 10 Mm and a lifetime of around 1 hour. The next scale is the *supergranulation* discovered by Leighton et al. (1962) (cf. Hart 1956). Its average cell size is 20–30 Mm and the average lifetime is about one day. Finally, the discovery of *giant cells* extending 40–50 degrees in longitude and less than 10 degrees in latitude, with a lifetime of about 4 months, was announced recently (Beck et al. 1998).

Here we investigate mesogranulation. It has been detected in a variety of ways. November et al. (1981) used filtering techniques to isolate mesogranulation from granular and supergranular patterns. Oda (1984) found that active granules (characterized by a succession of expanding granules followed by fragmentation) form a pattern which outlines mesogranules. The mesoscale spatial organization is also seen statistically in the locations of granules when they are separated into large and small granules (Muller et al. 1990; Brandt et al. 1991) bright and dark, expanding and contracting granules, etc. (Brandt et al. 1991).

The most powerful technique traces the direction and magnitude of local flows over the solar surface by sprinkling floating test particles on it which behave, much like corks on water and are therefore called corks. These corks are then followed while they are swept along by the horizontal motions of successive granules and intergranular lanes. If followed for a sufficient duration, such artificial corks are found to gather at the edges

Send offprint requests to: S.R.O. Ploner (ploner@linmpi.mpg.de)

of mesogranules (Brandt et al. 1988, 1994). Finally, the convective character of mesogranulation is confirmed by the phase relation between the intensity and radial velocity modulation which they exhibit (Deubner 1989), although a power increase cannot be detected at mesogranular scales (Straus & Bonaccini 1997) in contrast to supergranulation.

Various proposals have been made so far to explain these different horizontal scales of convection observed on the solar surface. The most widely known explanation, offered in standard text books (Foukal 1990; Stix 1991), stipulates that the horizontal patterns of granulation, mesogranulation and supergranulation reflect the presence, at different depths below the surface, of the ionization zones of hydrogen and neutral and singly-ionized helium (Simon & Leighton 1964). In particular, mesogranulation is thought to be the surface manifestation of convection cells driven by the superadiabaticity that is caused by the partial ionization of neutral helium, which indeed occurs at a depth below the solar surface that corresponds roughly to the horizontal size of mesogranules. Increasingly larger cell sizes are also possible with depth since the pressure and density scale height increases. More mass can therefore flow off horizontally, allowing for larger, coherent upflows (Stein & Nordlund 1989). The numerical simulations of Stein & Nordlund (1989, 1998) show that the size of the convection cell does indeed increase with depth. This is achieved by the merging of individual downflow lanes at depth greater than 1000 km. The pressure fluctuations associated with these large subsurface cells may advect smaller cells at the solar surface thereby making the mesoscale cells accessible to observations.

2. Results

Numerical simulations of the upper solar convection zone and lower atmosphere have been very successful in providing a physical understanding of the processes that produce the solar granulation (see the reviews by Spruit et al. (1990) and Spruit (1997)). Here we describe an extension of such simulations to include mesogranulation. The phenomenon requires a larger simulation extent and duration, while maintaining the high temporal and spatial resolution needed to reproduce granules properly. To keep the computational expense within reasonable limits we reduce the spatial dimensions of the simulation from three to two. Although solar convection is definitely a three-dimensional phenomenon, such two-dimensional simulations reproduce many of the known properties of granules (Steffen & Freytag 1991; Gadun et al. 1999; Ploner et al. 1999).

Our simulation covers 17.85 Mm in the horizontal direction and ran for 5 solar hours. On average around 10 granules are present in the computational domain at any given time, so that the complete evolution of over 400 granules can be followed (further details are provided by Ploner et al. (1999) and the references therein). The computational domain is large enough in the horizontal direction to harbour a mesogranular pattern. However, since the original motivation was to study the evolution of individual granules, the simulation covers only 2 Mm in the vertical direction and reaches only 1.1 Mm below the solar surface. It is only well below this depth that helium starts to ionize significantly and downflow lanes begin to merge sufficiently (at least in 3-D simulations). It was therefore with considerable surprise that we found mesogranulation to be present in our simulation when using the same criteria that are employed for its identification in observational data.

Fig. 1 displays the continuum intensity emerging from the simulations as a function of space and time, Fig. 2 the vertical velocity at a constant height near the solar surface. The location on the sun is drawn along the horizontal axis, time increases in the vertical direction. The pattern formed by the dark, downflowing (i.e. red shifted) lanes in the space-time diagrams is reminiscent of a river system: new lanes are constantly formed, but very rarely end. Rather, the number of lanes diminishes through merging. Granules are bright areas in Fig. 1, corresponding to upflowing (i.e. blue shifted) areas in Fig. 2, and are bounded on each side by an intergranular lane. The start of a new lane corresponds to the splitting of a granule into two new granules; the merging of two lanes marks the disappearance of a granule.

One of the noteworthy features of Figs. 1 and 2 is the presence of so-called active granules (Oda 1984), i.e. granules which expand and split consecutively many times (more precisely, at least one of the new granules formed by the fragmentation itself splits again and so on over a number of generations). Active granules often border on downflow lanes into which other lanes merge only from the side facing away from the active granule.

Fig. 3 is a more schematic version of Fig. 2. Intergranular lanes (identified here with downflows) are shaded black. The white areas in Fig. 3 are active granules, the remaining granules are shaded grey. According to Oda (1984) the location of active granules forms a pattern that outlines mesogranules, an observation that is consistent with the pattern produced by active granules in Fig. 3.

Observers have also isolated mesogranules by following horizontal flows on the solar surface using local correlation tracking (November et al. 1987) on image sequences. In this technique, local displacement vectors are determined by spatial correlation of small segments of subsequent images so that granular features are followed as they move over the solar surface. Longer-duration flow patterns (which need not be true hydrodynamic flows) are then displayed by introducing artificial corks that float at the solar surface and follow the motions of the individuals granules. The corks are initially distributed homogeneously at the solar surface, but end up at sites of convergence in the larger-scale flow pattern.

Since we are analyzing a 2–D simulation we employ a slightly modified technique. We distribute our corks not only uniformly in space (at a fixed height) but also in time. I.e. the whole area seen in Figs. 1 and 2 is filled uniformly with corks. We then follow the evolution of each cork from one time step to the next by shifting its vertical position in the figure (the time) by the time step and its horizontal position by a distance that is the product of the time step and the local horizontal gas velocity. This process is then iterated. After each iteration the corks have aged by a time step. A space-time snapshot, made after a certain

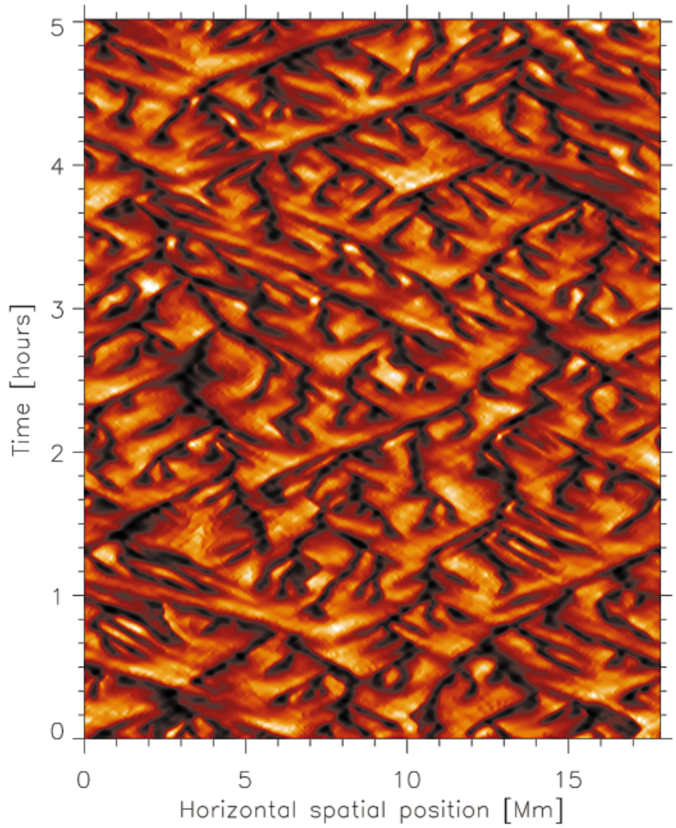

Fig. 1. Evolution of a simulated slice of the solar surface as seen in the continuum intensity at 5000 Å. Time increases in the vertical direction. The dark lanes correspond to dense, cool, downflowing gas. New lanes start individually, but end almost exclusively through merging with other lanes. Note that most gaps in the lanes are artifacts introduced by a wave-cleaning procedure applied to the output of the simulation (for details see Ploner et al. (1999)).

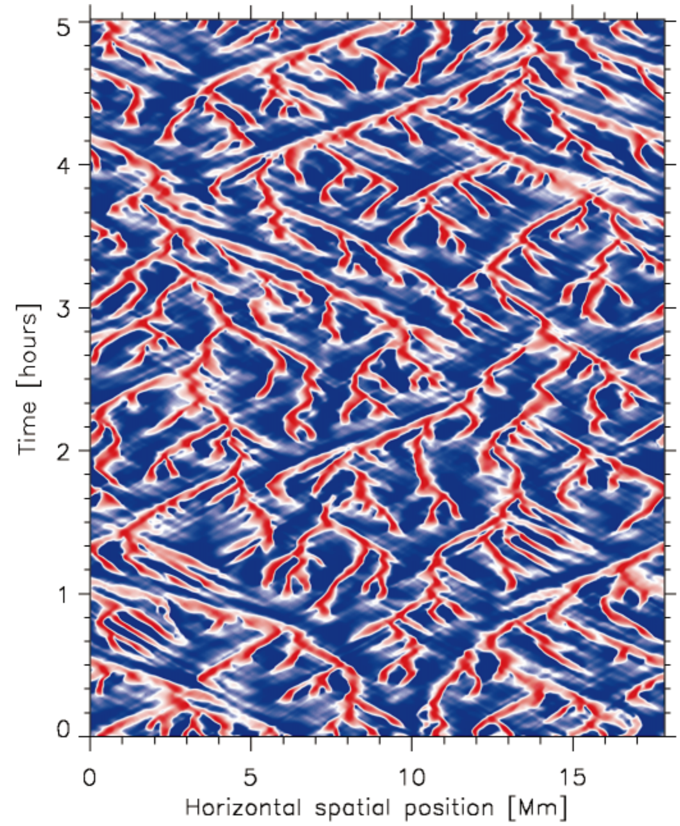

Fig. 2. Image of the vertical velocity at a constant height approximately 100 km below the surface. Blue shading corresponds to upflowing, red to downflowing gas. Darker color indicates larger velocity amplitude. A comparison with Fig. 1 reveals the correspondence between bright granules and upflowing gas.

number of iterations, shows corks of a given age, i.e. corks that have been allowed to follow the flow for a certain number of time steps.

The red dots in Fig. 3 represent corks that have aged for 50 min. Within this time they have all converged into a few downflowing lanes, which are on average 7 Mm apart. The positions of the corks generally lie close to chains of active granules. This provides further confirmation of the presence in our simulations of mesogranulation, as defined by observational criteria.

The intergranular lanes in which the corks collect after a number of granule lifetimes, i.e. those that make up the mesogranular borders, differ from the remaining intergranular lanes. They possess higher density, pressure and horizontal velocity amplitudes, are broader and contain slightly stronger downflows. These differences are related to the presence of active granules neighbouring the former lanes, since the larger pressure excess is required to deflect the strong horizontal flows associated with fragmenting and in particular active granules (Ploner et al. 1999).

The distribution of corks in Fig. 3 can be used to determine the lifetimes of mesogranules. Although the deduced lifetime of a mesogranular-cell depends somewhat on how long the corks are allowed to evolve, it is found to be on the order of 1–2 hours. This compares well with the recent observational work of Roudier et al. (1998), who give e-foldings lifetimes of between 40 minutes and 2 hours.

Fig. 3 also indicates the evolution of the size and location of mesogranules (Muller et al. 1992). Much like granules (Dialetis et al. 1986; Ploner et al. 1999) the simulated mesogranules die either by fragmentation or dissolution. A mesogranule dissolves when two mesogranular lanes (characterized by the red dots in Fig. 3) merge. An example is seen in Fig. 3 at time 2 h 45 min at 14.5 Mm. Other mesogranules appear to die by fragmentation, although the exact time and place cannot be determined with sufficient accuracy using corks. The signature of a fragmenting mesogranule is the formation of a new mesogranular lane. These two modes of death for mesogranules represent a prediction of our simulation that can be tested observationally.

Brandt et al. (1991) have made statistics of granule properties as a function of their location within a mesogranule. They find that there is a 6–9% excess of bright, long-lived and rapidly expanding granules in the interiors of mesogranules relative to their edges. Before comparing with these observations we spatially smeared the intensity pattern emerging from the simulation by 0.3″ in order to take into account the finite spatial

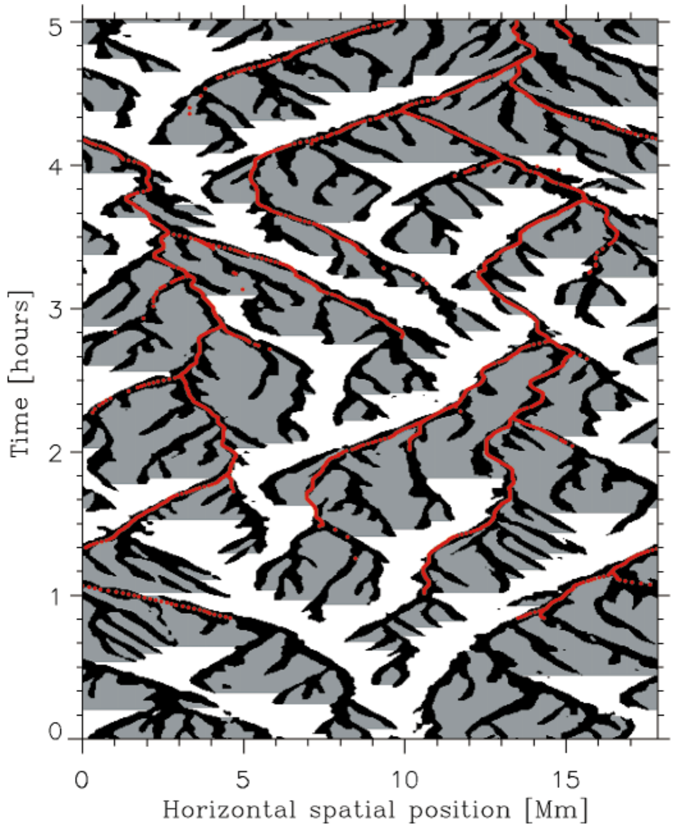

Fig. 3. Same as Figs. 1 and 2, but now with the downflowing gas shaded uniformly black. Also, active granules (plotted white) are distinguished from the rest (grey). "Active" granules are defined here as fragmenting granules, at least one of whose fragments splits again and so on for two or more generations. The other group (grey) consists of the remaining fragmenting granules and all dissolving granule (i.e. granules that become smaller with time and disappear at the junction of two lanes). The positions of the corks with an age of 50 min have been added as red dots. The corks are idealized test particles that were initially sprinkled uniformly over the space-time image and then allowed to float at a fixed height for 50 Min. In this time they moved with the horizontal flow field without influencing it and without interacting with each other. Multiple corks that land at the same location in space and time evolve like a single cork henceforth. This implies that with growing age the number of distinguishable corks diminishes since they become concentrated into increasingly fewer downflow lanes. The distribution of corks at age 50 min is independent of the initial cork distribution and density.

resolution of the telescope and the degradation introduced by the turbulence in the earth's atmosphere. After this smearing the smallest granules could no longer be isolated and were neglected in the subsequent analysis. We then find that longer-lived and brighter granules prefer the interior of the mesogranules over the boundaries by 3% and 18%, respectively. The large granules show the opposite preference by 6% and the rapidly expanding granules exhibit no preference. The thresholds for brightness, granule size and rate of expansion were set such that approximately 30% of all granules fulfilled them. Given that in our simulation the above statistics are based on 100 granules or less, differences of up to 10% with the results of Brandt et al. (1991) are not significant. Hence we can only say that the simulation is compatible with the results of Brandt et al. (1991) while admitting the need for better statistics in order to obtain a more stringent test.

The final analysis which we repeated is the one with which November et al. (1981) originally discovered mesogranulation: the application of a 3′′ and 15 min filter to the vertical velocity map in the middle or upper photospheric layer of our simulation uncovered a pattern with a horizontal scale of 5000 km, corresponding roughly to the mesogranular scale discovered by November et al. (1981).

3. Discussion

The most important conclusion resulting from our work concerns the interpretation of the observed phenomena identified with mesogranulation. Our simulation suggests that the pattern is actually produced within 1 Mm of the solar surface, a layer in which hydrogen is partially ionized and which harbours the high superadiabaticity that drives granulation (Rast 1999). In particular, our model is too shallow to include the layers in which helium becomes singly ionized, in which the pressure scale height increases sufficiently to allow for larger cell sizes, or in which individual downflow merge lanes. It nevertheless reproduces the observed properties of mesogranules. The shallowness of the model implies that mesogranulation is not exclusively a consequence of the helium ionization zone or of the subsurface increase of pressure and density scale heights.

Recently, the importance of the solar surface for convection in general and granules in particular has gained appreciation (Stein & Nordlund 1989; Spruit 1997; Rast 1999; Ploner et al. 1999). Our simulation suggests that mesoscale cells at greater depths Stein & Nordlund (1989, 1998), formed from the merging of downflows, are not the main drivers of the mesogranulation observed at the solar surface. We expect that cooling at the solar surface plays an important role in creating mesogranules and probably supergranules, just as it does for granules. Nevertheless, concrete mechanisms for producing convective cells with different scales at boundaries such as that formed by the solar surface (Cloutman 1979; Getling 1992) need to be studied in detail.

The present results point out the need to simulate observed larger-scale structures such as supergranulation, in order to establish whether they are surface-driven as well. Recent local helioseismic reconstructions suggest that the supergranular horizontal velocity patterns visible on the surface do not persist over more than a few Mm in depth (Duvall et al. 1997).

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