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Spatio-temporal patterns in solar surface convection

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Abstract. The solar plasma, under the control of convective motions, concentrates or diffuses the magnetic field emergent on the solar surface. The convection and magnetism, closely interacting, govern the activity we observe on the Sun. Commonly, on the solar surface, three different convective scales are indicated: the *granulation*, with a typical length of about 1-2 Mm, the *mesogranulation*, that ranges from 3 Mm to 10 Mm, and the *supergranulation*, with typical length scales of 20-30 Mm.
Recently, the physical framework of convection has been challenged and the processes at the base of the formation and evolution of solar features have been remarkably re-examined. In fact, even though in various measure, for all three scales a "classical" convective origin seems not sufficient to hold account of the complex observational and theoretical scenery. The recent progresses in observational techniques, laboratory experiments, and numerical simulations produce a more complex scheme where hydrodynamic instabilities, hard-turbulence regimes, cooperative evolution, play a dominant role in the description of onset and evolution of observed spatio-temporal patterns in the Sun.
After a brief review of the physics involved in the convection onset in the solar interior, some recent conclusions related to the three different convective scales are discussed.

Key words. Sun: solar convection - Sun: photosphere

1. From convective instability to the formation of patterns

The convective spatio-temporal patterns present on the surface of the Sun are produced by rolls, cells, and patches of cells that evolve and interact mutually. As well, solar convection and magnetism, closely interacting, govern the activity of our star and ultimately modulate the whole heliosphere.
The physical mechanism at the origin of the convective instability is the buoyancy produced by plasma density fluctuations in the deeper layers of the Sun. This buoyant force onsets mounting warm matter flows that rise toward the surface and overshoot into photospheric stable layers producing different observable features (Bray, Loughhead, Durrant (1984), Spruit, Nordlund and Title (1990)).
The classical scheme of buoyancy-driven convection follows by the Lord Rayleigh

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explanation (1916) of the famous experiment accomplished by Bénard. The theory, nowadays known as Rayleigh- Bénard convection, though superceded in later years (Pearson (1958)), has played a crucial role in guiding both theory and experiment towards an understanding of the emergence of complex dynamics from dissipative (i.e. far-from-equilibrium) systems (Cross and Hohenberg (1993), Paul et al. (2002)).
Following this scheme, a viscous fluid heated from the bottom and cooled at the top in a gravitational field, produces a Bénard pattern dues to the arrangement of patches of convective cells. The formation of the cells does not follow automatically. In fact, the convection onset depends on the physical properties of fluid, its depth, and the temperature gradient. In other words, the fluid remains uniform (spatial invariance) and steady (temporal invariance) until some critical conditions are fulfilled. Really, the onset of convection has to take into account at least two more modes of energy dissipation: 1) the *thermal conductive transfer* between the plasma worm packet and the surrounding plasma, that decreases the temperature difference (i.e. density), and 2) the *viscous drag*, between the convective cell and the surrounding plasma, that stops the motion of the cell itself. It is indispensable that the buoyant force, produced by the temperature gradient, exceeds, of a critical amount, the dissipative forces of heat diffusion and viscous drag to guarantee the outbreak of convective flow.
The status of the fluid could be quantitatively described by a nondimensional number R, called the Rayleigh Number, which is the buoyant force divided by the product of the rate of heat diffusion and viscous drag.

$$R = \frac{g\alpha d^3 \Delta T}{\nu\kappa} \quad (1)$$

where: g is the acceleration of gravity, α is the coefficient of thermal expansion, d is the vertical length scale, ΔT is the temperature difference between the planes, ν is the *kinematic* viscosity and κ the thermal diffusivity. For the inner Sun R is of the order of 10^{23}. When R exceeds a critical value of Rayleigh Number R_c, convection occurs.
If the Rayleigh Number represents a quantitative measure of when the switch from conductive to convective transport happens, i.e. the dominant energy transport mechanism becomes convection, a further nondimensional number, the Nusselt number Nu, represents the efficiency of convective heat transport with respect to the thermal diffusive one.

$$Nu = \frac{F_{conv}}{F_{diff}(\bar{v} = \bar{0})} > 1 \quad (2)$$

When refereed to a star, the usual criterion adopted to investigate the convective instability derives from a *blob theory* that study the fluctuations of an average state (Schüssler 2002). If we consider the rising matter packets (blobs) reported in Fig. 1, we can define three different characteristic times related to three different physical properties of the blobs:

- Blob timescale: $\tau_i = d/v$

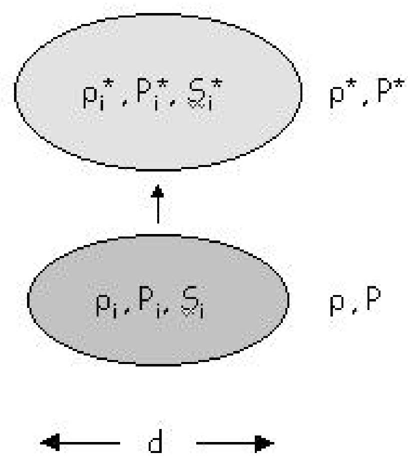

Fig. 1. Scheme of a convective blob moving upward. The symbols ρ, P, and S represent, respectively, the density, the pressure, and the entropy of the plasma. The subscript i refers to the *inner* plasma blob.

– Thermal timescale: $\tau_{th} = (c/\sigma)d^2$
– Dynamical timescale: $\tau_{dyn} = d/c_s$

where: d is the typical dimension of the blob, v is the vertical velocity of the blob, c is the specific heat, σ is the thermal conductivity, and c_s is the speed of sound. Since the two following relations between the different timescales exist:

$$\tau_i \ll \tau_{th} \Rightarrow S_i = S_i^*$$
$$\tau_i \gg \tau_{dyn} \Rightarrow P_i = P_i^*$$

we can assume that, at least in the interior of the Sun, the convective elements rise adiabatically, i.e. no exchange of energy occurs, and that they evolve in equilibrium of pressure with the surroundings. The instability follows from the request $\rho_i^* < \rho^*$. If we include in the latter relation the equation of state for the plasma we obtain the *Ledoux* criterion for dynamical instability:

$$\frac{dT}{dr} < \left(\frac{dT}{dr}\right)_{ad} + \frac{T}{\mu}\left[\frac{d\mu}{dr} - \left(\frac{d\mu}{dr}\right)_{ad}\right] \quad (3)$$

In a region with homogenous chemical composition, i.e. $\frac{d\mu}{dr} = 0$, the *Ledoux* criterion reduces to the famous *Schwarzschild* criterion. But for a few exceptions, like for example the precise determination of the border of a convective zone, both the criteria could be evaluated very easily by using the local values of P, T, and ρ without bothering other parts of the star (Kippenhan Weigert (1994)).

Nevertheless, these instability criteria, that are useful to investigate the conditions required for the onset of convective motion in the deeper layers of a star, cannot explain all the observed features of the fully developed convective flow emerging at the solar surface.

In fact, when the critical Rayleigh number is exceeded and the convective instability sets in, the system *responds* to the simultaneous attempt, from the hot layer to arise and from the cold upper layer to go down, performing a bulk movement and separating itself into a pattern of convective cells. In each convective cell the fluid rotates in a closed cycle and the direction of rotation alternates with successive cells. It is worthy to note that, locally, individual plasma particles move quite randomly, while, a large scale correlation among particle movements emerges and convective cells exhibit a statistical average behavior.

Fig. 2. Convective pattern, illustrated by contours of the thermal perturbation, arranged from Paul (2002). Dark features represent cool descending fluid and white features warm ascending fluid.

The origin of *interesting forms* in such dissipative systems, as for example the colored spirals of Belusov and Zabotinski or the pattern reported in Fig. 2 obtained by numerical simulation of Rayleigh-Bénard convection (Paul et al. (2002)), requires elaborated models of pattern formation (Prigogine and Kondepudi (2002), Cross and Hohenberg (1993)) in order to be interpreted. For our purpose, it is important to notice that these systems manifest a macroscopic order (i.e. spatial correlations) and the initial spatial invariance, or symmetry, is break out. This suggests the existence of correlations, that is to say, of statistically reproducible relations between distant parts of the system (Nicolis (1989)) .

2. Laboratory and numerical experiments

In the previous section the Rayleigh number R has been introduced as a parameter describing the status of the physical system in which the convection develops. If the value of R grows, the system experiments abrupt changes in the efficiency of heat distribution and in the complexity of the flow. Roughly speaking, when R increases, the system seems to develop more and more "disorder". After the Kolmogorov's theory of turbulence five patterns of flow were recognized: still, steady convection, periodic convection, chaotic convection and turbulent convection. Essentially what Kolmogorov did was explain the flow pattern and transport properties of turbulence and distinguish turbulence from chaotic flow patterns. However, experiments in gaseous and liquid Helium at low temperature, started in 1980s (Libchaber (1987), Chavanne et al. (2001)), changed the experimental study of turbulence theory and led to conjecture that Kolmogorov turbulence, defined by classical theory, could be divided further into "soft" turbulence and "hard" turbulence (see Fig. 3), thus making six recognized patterns of flow (Glazier (1998)). Soft turbulence, $R >\sim 10^5$ is characterized by a power law $Nu \propto R^{1/3}$, while for the hard turbulence the *2/7 regime*, i.e. $Nu \propto R^{2/7}$, is expected. The patterns characterizing turbulent convection become seven if it will be demonstrated the existence of an *ultra-hard* turbulence regime (Siggia (1994)) that could have important consequences in the calculations of thermal transport in stars (Glazier (1998)).

Though the values of R investigated in laboratory do not exceed $10^{14} - 10^{15}$, still several order of magnitude below the values we expect in stellar interior, and do not satisfy physical properties of stellar structure, as stratification and boundaries conditions, nevertheless this picture of convective turbulence has significant astrophysical relevance, as recently discussed by Spruit (1997). This new paradigm shows coherent structures of buoyant plasma (threads, plumes, thermals) connecting top and bottom surfaces. More in detail, the structure of the convective region appears crossed by filamentary features that drive the flow, while the non-buoyant fluid between remains passive and has zero temperature fluctuations. Fortunately, advances in parallel computers, numerical algorithms and data storage are such that direct numerical simulations of the full three-dimensional time dependent Boussinesq equations are possible for experimentally realistic situations. So, numerical simulation have been accomplished, in the same conditions of the laboratory experiments, in order to investigate the fluid behavior in all its details (Kerr (1996)). Although these simulations, owing to present limits in computer capabilities, could simulate physical systems with $R \simeq 10^7$, nevertheless the results agree closely with experiments and confirm the *thready* nature of the experimental convective flow (Nordlund and Stein (1996), Spruit (1997)), even thought with different opinions about the exact role played by hard-turbulent regimes in the solar atmosphere (Nordlund and Stein (1996)).

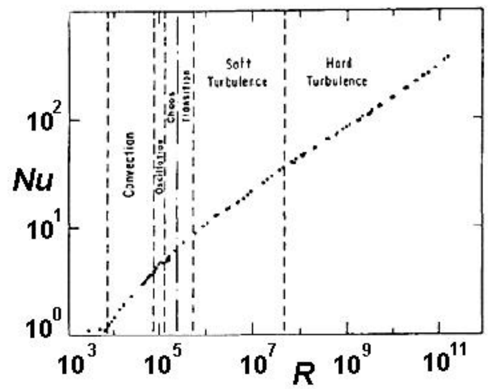

Fig. 3. Nusselt number Nu as a function of the Rayleigh number R. Vertical dotted line divide the different regimes of convection. Adapted from Libchaber (1987).

For our purpose different main conclusions could be extracted from this physical framework:

- A wide continuum of scales of motion is present, from the supergranular scales down to the resolution limit (Petrovay (2001)).
- The upward and downward threads of buoyant fluid are surrounded by layers of strong shear where small scale turbulence, especially below the resolution limit, may be concentrated (Nesis et al. (1997)).
- Granules are but one example of the exaustive family of coherent structures in turbulent flows (Petrovay (2001)).
- The size of granules is controlled by the relative position of descending plumes. As a matter of fact, 2D numerical simulations, in a adiabatic layer, show that when the separation between two neighboring plumes exceeds a critical limit, a new plume spontaneously forms in between (Rast (1999)).
- Granules, or better the associated small scale downdrafts, provide the driving force for the large scale flows (Nordlund, private communication in Spruit (1997)).

3. Small scale convection

Small scale convective features occurring over the solar surface (i.e. granulation phenomenon) could be fashioned in the physical framework described in the previous sections. The granular pattern (Fig. 4) is drove by strong descending channels consequence of hydrodynamic Rayleigh-Taylor instabilities taking place at the top of the photosphere. In these layers colder collapsing matter is smoothly replaced by warm plasma. As a consequence, the familiar picture of warm bubbles arising from the innermost layers of the solar structure is not longer applicable.

In the last years, a considerable amount of 2-D and 3-D numerical simulations of fully compressible convection have been done in order to reproduce and understand observed granular features (see Gadun et al. (2000) and references therein). Different aspects of surface convection have been investigated in these numerical experiments, ranging from spectral properties of photospheric lines to granular dynamics. Nevertheless, the important subject of small scale convective geometrical texture, i.e. the disposition of specific granules, has been disregarded. This topic, and particularly the possible existence of some kind of regularity in the granular pattern, is actually inseparable from physical properties of convection. In recent times, Getling and Brandt (2002) investigated this argument. In their work the authors discuss the presence, in time averaged photospheric brightness fields, of quasi-regular structures of the photospheric flows. Particularly, they report that *averaged images are far from completely smeared and contain a multitude of bright, granular-sized blotches even if the averaging period is as long as 8 h.* This fact has been used as forthright evidence that granules prefer to come from preferential sites. Moreover, the associated patterns display relatively regular arrangements that appear as the patterns observed in experiments on Rayleigh-Bénard convection. The important conclusion is that in the solar atmosphere a previously unknown type of self-organization is revealed and *granules are associated with overheated blobs carried by the convective circulation.*

The basic idea that small scale convection implies some kind of self-organization and topological order (geometrical texture) has been challenged by Rast (2002a). In his *comment on "Regular structures of the solar photosphere"*, the author shows that all the granulation properties reported in Getling and Brandt (2002) are consistent with a, *non-physical* model of, completely random and changing flow pattern of typical granular lifetime. Therefore, the main conclusion is that the observed features could be simply interpreted as statistical properties of a granular random field.

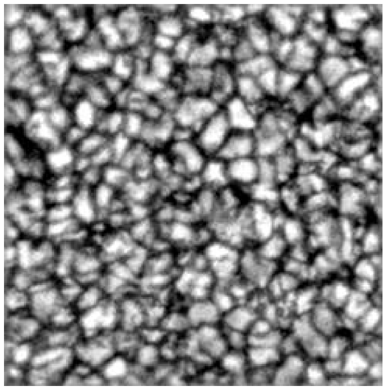

Fig. 4. Broad band image acquired at THEMIS telescope in IPM observing mode. The FoV is about $30'' \times 30''$.

In order to study the topological properties of convective flows, it is possible to use quantitative statistical methods able to distinguish regular textures automatically (Consolini et al. (2003), Berrilli et al. (2003)). This approach suggests the existence of regularity in the photospheric granular pattern due to the existence of correlations between convective structures, that is to say, of statistically reproducible relations between distant parts of the system as suggested by Nicolis (1989).

4. Large scale convection

In the section 2, the cleverness of numerical simulations to reproduce the smallest features of cellular convection has been discussed. Conversely, the flows associated to larger scale convective cells, for example supergranular pattern (Fig. 5), are not wholly reproduced by numerical models. Consequently, their developments remain inexperienced.

The mechanism for convection, presented in the previous sections, shows as the granulation is taken to be the result of continual formation of downward plumes induced by hydrodynamical instabilities on the solar surface. But what is the origin of larger scales cellular patterns? Concerning the origin of larger flow patterns on the Sun, including mesogranulation (November et al. (1981)) and supergranulation (Leighton, Noyes, and Simon (1962)) structures, mainly two physical mechanisms are invoked:

1. collective interactions between smallest flows, and 2. a more traditional explanation where larger convection cells are drove by the deeper second ionization of Helium. We can investigate these hypothesis using the enormous quantity of experimental and numerical tools today available.

The non-convective origin of the *mesogranulation* phenomenon has been pointed out, in two different papers, by Straus, Deubner, and Fleck (1992) and by Straus and Bonaccini (1997) bringing into play, respectively, the overshoot in the middle photosphere and internal gravity waves in the solar atmosphere. Again, a non-convective origin of greater scales has been invoked by Rast (1995). Here, the author argues that the granulation dynamics, particularly the powerful process of *exploding* granules, may possibly explain the observed correlation between the spatial distribution of such structures and mesogranular flows. Therefore, mesogranulation and supergranulation are both suggested as the resulting manifestations of small scale convective flows. Rieutord et al. (2000) presented a similar conclusion. In their work the mesogranulation is regarded not as a true scale of solar convection but rather as originated by the combination of the effects of both highly energetic granules, as stated by Rast (1995), giving origin to intense positive divergences, and averaging effects of data processing.

Shine, Simon, and Hurlburt (2000), analyzing a very long timeseries of flow maps of photospheric motions derived from MDI-SOHO dopplergrams, investigated horizontal divergence maps. The authors concluded that mesogranules appear as local maxima in flow maps, while the same divergence maps clearly show the advection of these mesogranules within each supergranule. The dynamics of super-

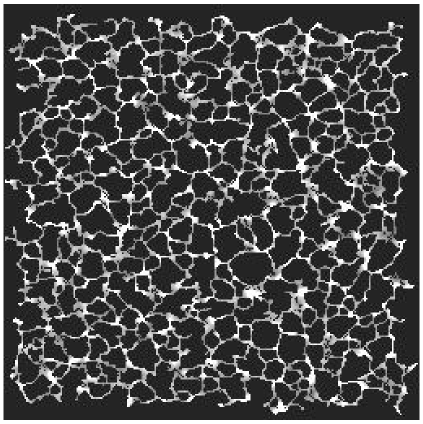

Fig. 5. Ca K network as extracted from a PSPT-OAR image using the *i*-MAT (skeleton) procedure described in Berrilli et al. (1999). The dimension of the frame is about $8.5' \times 8.5'$.

granulation is drove by strong divergences, while narrow boundaries of negative divergence outlining the supergranules themselves.

The viewpoint that the mesogranules owe their origin to collective interactions between the granules is derived, by numerical experiments on turbulent convection, by Cattaneo, Lenz, and Weiss (2001). In their work, the authors supported this conclusion analyzing the results indicated by three-dimensional Boussinesq convection simulations in a layer with a very large aspect ratio.

Another approach to reproduce key properties of both granules and mesogranules is represented by 2D simulation made by Ploner et al. (2000). In this case numerical models resolves horizontal scales that extent up to 5-10 Mm and seem to demonstrate that mesogranulation is driven close to the solar surface, as supposed for granulation, and therefore rules out the classical explanation of mesogranulation as cellular convection driven by superadiabaticity in the deeper layer, where neutral Helium ionizes. Conversely, a convective origin of mesogranulation is supported by Lawrence, Cadavid, and Ruzmaikin (2001) that applied a wavelet spectral analysis to a 2-hour sequence of 120 SOHO/MDI, high-resolution, Doppler images near disk center, and conclude that the wavelets allow the detection of individual local flow patterns corresponding to convection cells.

Obviously, the results ruled out for mesogranular scales also casts doubt on the traditional explanation of supergranulation. Generally, the deeper second ionization of Helium is invoked in order to explain larger convective cells with diameters of 20-30 Mm. However, it results evident that small scale photospheric motions can act together, as indicated by Rast (1995), to organize supergranular flows. It results necessary, in order to resolve this puzzle, to disentangle the magnetic network contribution to the continuum intensity from that of the presumed underlying convective supergranular flow **?**. Preliminary results, derived from PSPT-RISE dataset, indicate that while the magnetic network contribution to the continuum intensity is small but readily measurable, the convective contribution lies very near or below detection limits and no clear conclusions could be achieved.

5. Conclusions

It can be stated that granular scales exhibit convective regime where the thread nature of the downward plumes, associated to hard-turbulent convective regimes, plays a fundamental role in the formation of granular pattern. On the contrary, the basic origin of largest pattern observed on the solar surface remains unsolved and more precise observations and numerical simulations are necessary.

Moreover, it results confirmed the basic relevance of solar convection study in order to investigate the physical behavior of astrophysical plasma under the action of turbulent convection, being the present laboratory and numerical capabilities order of magnitude below the actual physical conditions present in the solar interior and surface.

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