MHD SIMULATIONS OF THE SOLAR PHOTOSPHERE

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Abstract. We briefly review the observations of the solar photosphere and pinpoint some open questions related to the magnetohydrodynamics of this layer of the Sun. We then discuss the current modelling efforts, addressing among other problems, that of the origin of supergranulation.

1 Introduction

The solar photosphere is the only place in the Universe where we have a detailed view of stellar convection. Thermal convection is a well-known phenomenon that has been studied for more than a century, but in the case of stars it still owns many dark sides that prevent us from a full understanding. Unfortunately, convective regions of stars like the Sun are the seat of the magnetic activity, whose explanation requires strong investigations of flows where buoyancy, radiation and magnetic fields couple together.

Flows are thus complex, but their darkest side is their turbulent nature which implies the interaction between many scales either in the velocity field or in the magnetic field or between both. Handling such a multiscale phenomenon has become possible when computers have reached enough computing power so that numerical simulations be realistic on some side(s). The first work of [Nordlund (1985)] perfectly illustrates the emergence of interesting simulations coupling fluid dynamics and radiative transfer, and which could be compared to observations (line profiles). With the steady increase of computational power, such simulations have become the preferred tool of astrophysicists involved in fluid dynamical problems. More and more sophisticated simulations addressing the solar photosphere magnetohydrodynamics have emerged [Stein et al. (2009); Ustyugov (2010)].

Thus, in this short review, we first set up the stage provided by observations of the Sun and pinpoint some open questions. Then, we briefly describe the current modelling efforts, ending this work with some perspectives.

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2 Observations of the quiet Sun dynamics

2.1 Multiscale convection

It is well-known that solar convection is a multiscale phenomenon: first of all because it is a turbulent flow that naturally contains a continuum of scales and second because of some specificities of thermal convection in stars that single out some particular scales.

Among the specific scales, the most well-known is the granulation, discovered long ago by Nasmyth in 1860 (Bartholomew 1976) and which shows cells typically 1 Mm wide, lasting 500-1000s with velocities of order 1-2 km/s. As detailed below the physical origin of granulation is understood. This is not quite the case of the supergranulation which is the other specific scale arising in the convective flow visible at the Sun’s surface. This scale has also been known for quite some time, exactly since the work of Hart (1954). Unlike granulation, it is only visible via its horizontal velocity signature. Thus, dopplergrams like that of Fig. 1 readily show this feature. The typical length scale is around 30 Mm, with a time scale typically 1.8 days, meaning velocities about 400 m/s (we refer the reader to Rieutord & Rincon 2010 for a detailed review of solar supergranulation). For historical reasons, we only briefly mention mesogranulation, which has been searched for a long time as the intermediate scale between granulation and supergranulation. Results have been much controversial and we think that mesogranulation is most likely a ghost pattern emerging from data processing of delicate flow measurements (see Rieutord et al. 2000, 2010).

2.2 Magnetic fields

In the quiet photosphere magnetic fields are also present especially through the so-called “network” which is clearly seen with the chromospheric Ca\textsuperscript{+} K3 line. The network shows a cellular pattern covering the Sun (see Fig. 2), and coincident with the supergranulation cell boundaries, but with slightly smaller cells (e.g. Hagenaar et al. 1997). It has thus often been used to monitor the size variations of supergranulation. The origin of this field, which consist of flux tubes with a magnetic field up to 1kG, is not fully understood, especially its interaction with supergranulation. The situation is quite similar for the intra-network field, which is very disordered and with an amplitude in the range 50-200 G (Domínguez Cerdeña 2003).

Recently, Roudier et al. (2009) studied the evolution of “Trees of Fragmenting Granules” (TFG) and found that they were basically advected by the supergranular flow. Besides, using floating corks, they demonstrated that vertical magnetic fields always evolve to a patchy distribution along the supergranule boundaries. This enforces the relation between magnetic fields and supergranulation, suggesting that this feature is an emergent length scale building up when small magnetic elements are displaced by TFGs flow, occasionally colliding and aggregating to form larger magnetic clusters, which in combination with granulation can trigger the supergranular downflow structure.
3 Open questions

The observations, very briefly summarized above, raise many unsolved problems. The main one, but not the only one, is that of the origin of the supergranulation. The observational facts may be summarized by the schematic view displayed in Fig. 3. Many scenarios have been proposed to explain the existence of supergranulation (Rieutord & Rincon, 2010), but none of them is confirmed. At the moment, we (the authors) favour the idea that this feature of solar surface flows results from a large-scale instability of surface convection, likely influenced by the magnetic fields, as suggested by Fig. 4 (see also Rincon & Rieutord, 2003).

However, this question is most probably related to the origin of the intra-
network fields: are these fields generated locally by a small-scale dynamo? or reprocessed from active regions or just emerging from beneath? How do they relate to the cycle? Can we distinguish these various possible origins?

4 Current modelling efforts

4.1 Solar convection: a very turbulent flow

To really appreciate the difficulty of the modelling of flows in the solar photosphere, one should first realize how extreme are the numbers which control solar convection.

The Rayleigh number is the ratio between buoyancy, which drives the flows, and dissipative process (viscosity and heat diffusion). In laboratory experiment,
one hardly reaches $10^{11}$, while the Sun reaches $10^{22}$. Reynolds numbers in solar flows are typically around $10^{12}$, while laboratory experiment remain below $10^9$. This number is particularly interesting since it controls the ratio between the smallest (dissipative) scales and the most energetic ones (the one we see). Indeed this ratio scales like $Re^{3/4}$. This means that, for instance, granular flows for which $Re \sim 10^{12}$, own structures (vortices) whose size range from 1000 km down to 1 mm!

The extreme values shown by Rayleigh and Reynolds numbers are essentially due to the large size of the body. However, the fluid itself has intrinsic properties which are uncommon to Earth standards. The kinematic viscosity $\nu$ of the fluid is around $10^{-3}$ m$^2$/s (e.g. Rieutord, 2008), which is a thousand times larger than that of water. However, the heat diffusivity $\kappa$ is $10^5$ times higher because heat is carried by photons essentially and radiative processes are increasingly efficient when temperature raises. The point here is that the Prandtl number, $\mathcal{P} = \nu/\kappa \sim 10^{-5}$, which is very small compared to that of any terrestrial fluid (the lowest value known on Earth is that of mercury which is 0.025). The same occurs for the magnetic field diffusivity, controlled by the electric conductivity of the plasma. The magnetic Prandtl number is also very small, in the range $10^{-5}$–$10^{-2}$.

The values of all these numbers make a direct numerical simulation of solar convection strictly impossible with nowadays computers. Likely, this will remain the case for many many years, and actually such a DNS would not be so interesting except of being an experiment where one can play with huge statistics on all sorts of quantities!

Fig. 4. A schematic view of the kinetic and magnetic spectra that should be assessed by observations (from Rieutord & Rincon, 2010).
4.2 Current simulations

4.2.1 Granulation

Nowadays simulations of the solar photosphere (e.g. Stein & Nordlund 1998; Rieutord et al. 2002; Stein et al. 2009) do not take into account the very high values of the Rayleigh and Reynolds numbers. Their viscosity are actually of numerical origin and related to the mesh size. They thus belong to the category of Large Eddy Simulations (LES), which use artificial truncation of the turbulent spectrum.

These LES have however been able to reproduce the thermal structure of the surface layers of the Sun and especially granulation (we refer the reader to Beeck et al. 2012, for a very recent comparison of the codes). The very reason for this success is that the scale of granulation is such that the Péclet number is of order unity. It means that heat diffusion and heat advection are of the same order of magnitude, and therefore heat transport is correctly taken into account. Of course the Reynolds number is unrealistic: actually, a visual comparison between the simulated and observed granules shows that the latter ones are much more turbulent and slightly (by 10-15%) smaller (Roudier, private communication).

4.2.2 Supergranulation

The success obtained in modelling granules has triggered attempts to simulate supergranulation (Rieutord et al. 2002; Stein et al. 2009). Unfortunately, these attempts failed at exhibiting this feature of the solar convection. There are likely several reasons for that failure. The first one is the increased (over granulation) difficulty set up by the necessary size of the computing domain. The aspect ratio (width over depth) has to be increased sufficiently to give room to this structure. If we assume, which is not proved, that supergranulation is a surface phenomenon (like granulation), then computing boxes just need to be extended horizontally, ideally by a factor of order 30 (the ratio between supergranular and granular scale), meaning a factor 900 on the grid points. None of the simulations have made such a jump, therefore the granules computed in these supergranulation-intended simulations face an even greater numerical viscosity. Thus, if supergranulation comes form a large-scale instability of sub-structures, the reduced Reynolds number of the sub-structures (like granule), is likely to impede the development of such an instability. In addition, such big boxes require much more time to relax. As a consequence, if the simulations is on the verge of displaying the instability, the supergranulation pattern might not be seen just because the computation is not long enough!

4.2.3 Magnetic fields

In the previous simulations no magnetic field is included, however it might be crucial for the existence of supergranulation. Including magnetic fields is costly and therefore attempts in this direction have relaxed other constraints, essentially the size of the domain. For instance, Ustyugov (2010) includes magnetic fields but
uses a resolution almost twice smaller than \cite{Stein2009}. In addition, the run lasts a shorter time (48 solar hours instead of 64 s.h.). Finally, in this simulation, the magnetic field was not generated by a local dynamo, but given with initial conditions (an initial uniform vertical field). The results are nevertheless interesting as a structure like the network appears (see figure \ref{fig:5}, however the simulation is not long enough to tell whether this structure is statistically steady. Obviously, more efforts are needed in this direction.

Beside the large values of the kinematic and magnetic Reynolds numbers, another difference between simulations and actual stellar situations is the ratio between these two numbers, namely the magnetic Prandtl number $P_m$. Stellar values are small compared to unity, while simulations have displayed a dynamo when using either order unity values for $P_m$ \cite{Brandenburg1996} or values larger than unity \cite{Nordlund1992, Cattaneo1999}. At Reynolds numbers reachable by simulations, the dynamo disappears when the magnetic Prandtl number is realistic.

Actually, it seems that the critical value of the magnetic Reynolds number increases when the kinetic Reynolds number increases. This effect is expected since a higher kinetic Reynolds numbers means a stronger turbulence and thus a more effective dissipation. This effect does not facilitate numerical investigations. Recent work by \cite{Schekochihin2007} investigated a kinematic dynamo at low magnetic Prandtl number (down to $P_m = 0.07$), showing that velocity field and the magnetic have very different statistical properties. Figure \ref{fig:6} from \cite{Schekochihin2007} shows the positions of several dynamo simulations in a diagramme ($R_e$, $R_{em}$), delineating the critical line below which the dynamo instability disappears. Note that for this kind of flows, this critical curve $R_{em}^{crit}(R_e)$ is not monotonous. Another recent work by \cite{Buchlin2011}, used the simplified shell model and argued that the critical Magnetic Reynolds number remains finite as the kinetic Reynolds number tends to infinity. However both of the foregoing works are investigating kinematic dynamos and presently, nobody knows how such
Fig. 6. Positions of kinematic dynamo simulations by Schekochihin et al. (2007) using viscosity or hyperviscosity as a representation of the neglected small scales. The solid lines give the critical magnetic Reynolds numbers according to this prescription or from the work of Ponty et al. (2007).

low-$P_m$-dynamos saturate.

5 Perspectives

To conclude this short review, we would like to insist on the problems faced by Large-Eddy Simulations (LES) at simulating the solar photosphere.

Obviously, LES are still lacking of a good subgrid scale model to represent more faithfully the effects of small-scales that are not resolved by the simulations. Actually, this is a case of fundamental research in turbulence, which is much investigated in applied fluid mechanics, but not so much in astrophysics. The astrophysical situations are of course not amenable to laboratory experiments, but the numerous detailed observations that can be gathered from the Sun are very useful to give hints to models. For instance a determination of the magnetic energy spectrum completing the work of Abramenko et al. (2001), may be very helpful to find the origin of supergranulation.

Back to simulations of the photosphere, more detailed investigations are needed
to understand the interplay of a small-scale dynamo, its saturation at low magnetic
Prandtl number, and the basic advection of a background field. These are likely
questions for the next decades...

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