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Challenges of magnetism in the turbulent Sun

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Abstract. Three-dimensional global modelling of turbulent convection coupled to rotation and magnetism within the Sun are revealing processes relevant to many stars. We study spherical shells of compressible convection spanning many density scale heights using the MHD version of the anelastic spherical harmonic (ASH) code on massively parallel supercomputers. The simulations reveal that strong magnetic fields can be realized in the bulk of the solar convection zone while still attaining differential rotation profiles that make good contact with helioseismic findings. We find that the Maxwell and Reynolds stresses present in such a turbulent layer play an important role in redistributing angular momentum, with the latter maintaining the differential rotation, aided by baroclinic forcing at the base of the convection zone which is consistent with a tachocline there. The dynamo processes generate strong non-axisymmetric and intermittent fields and weak mean (axisymmetric) fields, but do not possess a regular cyclic magnetism. The explicit inclusion of penetrative convection into the tachocline below is modifying such behavior, serving to build strong toroidal magnetic fields there that may yield more prominent mean fields that have the potential of erupting upward.

Keywords. Sun: Convection, turbulence, Sun: rotation, Sun: magnetic fields, (magnetohydrodynamics:) MHD

1. Introduction

Understanding the Sun is a very challenging task given the very high accuracy and detailed observations of its surface and inner layers and the large range of temporal and spatial scales that characterize its turbulent dynamics. 3-D MHD simulations are a powerful tool to assess and understand the intricate interactions between convection, rotation, turbulence and magnetic field in the Sun, that we believe are at the origin of such a wide range of dynamical phenomena. For the last 20 years, helioseismic inversions of large-scale, axisymmetric, time-averaged flows in the Sun, such as its rotation profile or its surface meridional circulation, have provided important observational constraints on global-scale models of solar convection (Thompson *et al.* 2003). Such flows (averaged over longitude and time) have therefore been a primary focus (in particular the differential rotation profile) of simulations of the solar convection zone (Glatzmaier 1987; Miesch *et al.* 2000; Brun & Toomre 2002; Miesch, Brun & Toomre 2006). Similarly, the striking diversity and organisation of the solar magnetism, such as its 22-year magnetic cycle with sunspots following the well known butterfly diagram, and emerging at mid latitude and migrating toward the equator as the cycle proceeds, the existence of active longitudes for sunspot emergence, the presence of magnetic flux at all scales, etc..., push the solar physicists to develop and test a model explaining these puzzling properties.

Today the most commonly accepted scenario explaining the operation of the solar global dynamo is the *interface dynamo* paradigm (Parker 1993). It is based on the following underlying processes or building blocks: (*a*) The α-effect: the generation of the background weak poloidal field, either by cyclonic turbulence within the convection zone or by breakup of active regions. (*b*) The β-effect or turbulent transport: the transport of the weak poloidal field from its generating region to the region of strong shear, the tachocline either by turbulent convective plumes (Tobias *et al.* 2001) or by meridional flows. (*c*) The ω-effect: the organization and amplification of the magnetic field by differential rotation, particularly by large-scale rotational shear in the tachocline, into strong, isolated magnetic structures that are toroidal in character. (*d*) Magnetic buoyancy: the rise and transport of the large-scale toroidal field by magnetic buoyancy into and through the convection zone to be either shredded and recycled or to emerge as active regions. Self-consistent magnetohydrodynamic (MHD) simulations which realistically incorporate all of these processes are not yet computationally feasible, though some elements can now be studied with reasonable fidelity. More specifically in this paper we briefly report on the recent advances made by our group in modelling the dynamo blocks (*a*), (*b*) and (*c*) and in particular, how the inclusion of a stable shear layer at the base of the convection zone, i.e. the tachocline, can improve the realism of our solar global dynamo 3-D MHD simulations (see Brun, Miesch & Toomre 2004 (hereafter BMT04) and Browning *et al.* 2006 for more details).

2. Brief description of the numerical approach

We use the ASH code (anelastic spherical harmonic; see Clune *et al.* 1999, Miesch *et al.* 2000, BMT04), to solve the full set of 3–D MHD anelastic equations of motion (Glatzmaier 1987) in a rotating, convective spherical shell with high resolution on massively-parallel computing architectures assuming a LES-SGS approach. The anelastic approximation captures the effects of density stratification without having to resolve sound waves which would severely limit the time step. In order to ensure that the mass flux and the magnetic field remain divergenceless to machine precision throughout the simulation, we use a toroidal–poloidal decomposition (see BMT04 for more details). Our numerical model is a highly simplified description of the solar convection zone: solar values are taken for the heat flux, rotation rate, mass and radius, and a perfect gas is assumed. The computational domain extends from 0.72 to 0.97 $R_\odot$, for the purely unstable models discussed in §3 and from 0.6 to 0.97 $R_\odot$ for the models including a stable layer below the convection zone discussed in §4.

3. Simulations of magnetized convection without a tachocline

Starting from a purely hydrodynamic progenitor model of solar convection, we introduce a seed magnetic field in the simulation and let it evolve. We find that above a critical magnetic Reynolds number ($R_m^{crit} \sim 300$), the magnetic energy (ME) grows by many order of magnitude through dynamo action, then saturates, due to the nonlinear feed back of the Lorentz forces, to a value of about 7% of the kinetic energy (KE) and sustains that level for more than 3 ohmic decay times. Upon saturation, KE in the model has been reduced by about 40% compared to its initial value given by the purely hydrodynamic progenitor. This change is mostly due to a reduction of the energy contained in the differential rotation which drops by over 50%. By contrast, the energy contained in the convective motions only decreases by about 27%, which implies an increased contribution of the non-axisymmetric motions to the total kinetic energy balance. A detailed analysis of the redistribution of ME within its mean and fluctuating components reveals

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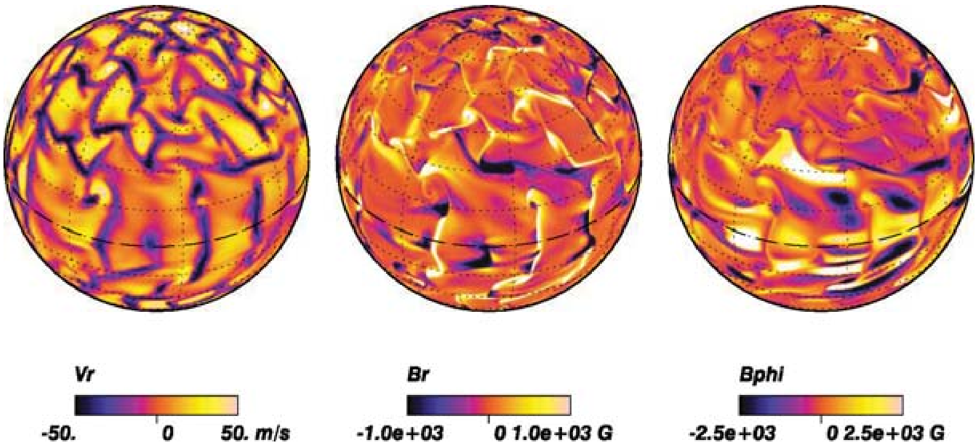

Figure 1. Snapshot using an orthographic projection, of the radial velocity (left), radial (middle) and longitudinal (right) magnetic field near the top of the domain for the purely unstable magnetized convection model. Typical field strengths are indicated, with dark tones corresponding to downward velocities and negative polarities. The dashed line indicates the equator.

that the magnetic energy contained in the mean-field components ($m = 0$) represents only 2% of total ME with the 98% remaining contained in the non-axisymmetric fluctuations. Most of the mean-field energy is in the toroidal field (1.5%), which exceeds the energy in the poloidal field by about a factor of three due to the stretching and amplification of toroidal field by differential rotation in the convection zone (the ω-effect). This ratio is smaller than in the Sun, where the mean toroidal field is estimated to be about two orders of magnitude more energetic than the mean poloidal field. This discrepancy can be attributed to the absence of an overshoot region and a tachocline, where toroidal field can be stored for extended periods while it is amplified by relatively large angular velocity gradients (see §4 below). For the non-axisymmetric fluctuations, the magnetic energy is approximately equally distributed among the toroidal and poloidal fields.

To illustrate the complex interplay between convective motions, differential rotation and magnetic fields, we display in Figure 1, the structure of the convection and magnetic fields realized near the surface ($r \sim 0.96R$) in the purely unstable model. The convective patterns are qualitatively similar to the hydrodynamic progenitor. The radial velocity (Fig. 1 left) is dominated by narrow cool downflow lanes and broad warm upflows, with a more isotropic behavior at higher latitudes (given the moderate level of turbulence of the progenitor case). The temperature fluctuations (not shown) exhibit a banded appearance most likely linked to an inner thermal wind, that contributes somewhat to the establishment of the differential rotation (see below), as well as it is well correlated with the radial velocity (cold going down and hot going up) thus transporting the heat outward. The radial magnetic field (Fig. 1 middle) is found to be concentrated in the downflow lanes, with both polarities coexisting next to each other, having been swept there by the horizontal (diverging) convective motions at the top of the domain. The Lorentz forces in such localized regions have a noticable dynamical effect on the flow, with ME sometimes being locally bigger than KE, influencing the evolution of the strong downflow lanes via magnetic tension that inhibits vorticity generation and reduces the shear, thus somewhat altering the angular momentum balance established in the progenitor solution. The magnetic field and the radial velocity possess a high level intermittency both in time and space, revealed by extended wings in their probality distribution functions and are quite asymmetric (BMT04). In Figure 1 right, we display the longitudinal

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magnetic field B_ϕ that appears to be more distributed and more patchy than B_r, with broad regions of uniform polarity, particularly near the equator, but nothing ressembling active regions. Further no clear symmetry or antisymmetry is apparent in contrast with observational evidence such as the solar butterfly diagram.

Our progenitor hydrodynamic simulation possesses a rather strong, solar-like differential rotation, with fast eqautor, slow poles and some constancy along radial lines at mid latitude, but no tachocline in this purely unstable case (BMT04, Thompson *et al.* 2003). With fairly strong magnetic fields sustained within the bulk of the convection zone in the magnetized case considered here, it is to be expected that the differential rotation Ω established in the progenitor will respond to the feedback from the Lorentz forces. The main effect of the Lorentz forces is to extract energy from the differential rotation (see above). This is reflected by a 30% decrease in the angular velocity contrast $\Delta\Omega$ between the equator and latitudes of 60°, but nevertheless $\Delta\Omega$ remains comparable to helioseismic inversions. The redistribution of the angular momentum in our shell reveals that the source of the reduction of the latitudinal contrast of Ω can be attributed to the poleward transport of angular momentum by the Maxwell stresses (see Brun 2004, BMT04). The large-scale magnetic torques are found to be 2 orders of magnitude smaller, confirming the small dynamical role played by the mean fields in our MHD simulation without tachocline. The Reynolds stresses now need to balance the angular momentum transport by the meridional circulation, the viscous diffusion and the Maxwell stresses. This results to a less efficient speeding up of the equatorial regions. Those results even though encouraging, confirm that the global dynamo is unlikely to be distributed only in the convection zone, and that it requires two different sites for the generation and organisation of the toroidal and poloidal fields, as anticipated by the interface dynamo scenario.

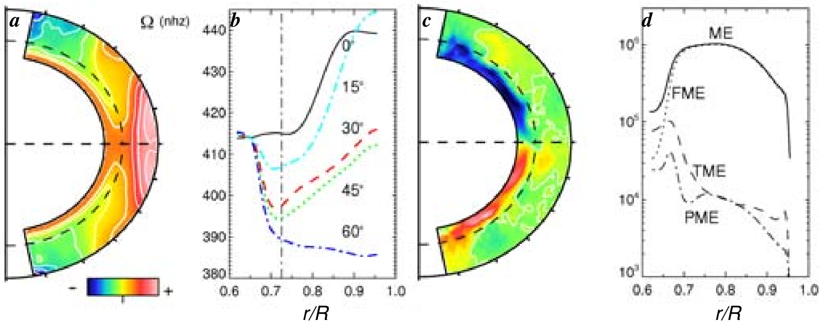

Figure 2. Azimuthal and temporal average of the angular velocity shown as contour plot (a) and radial cuts at indicated longitudes (b) and of the longitudinal (axisymmetric) toroidal field (c) for the model with a tachocline. In d) we display the horizontal average of the various components of ME, with in turn TME the toroidal mean magnetic energy, PME the poloidal mean magnetic energy and FME the fluctuating magnetic energy.

4. Influence of a tachocline on field generation and organization

One important feature that helioseismic inversions have revealed is the presence of the tachocline at the base of the solar convection zone. As stated in the introduction, the current solar dynamo paradigm favors the interface dynamo scenario (Parker 1993), i.e the site of generation of the poloidal field (located inside the convection zone) is spatially separated from that of the toroidal field (localized in the tachocline); with turbulent

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pumping, magnetic diffusion and/or large scale meridional flows linking both sites, and closing the dynamo loop. It is thus crucial to include a strong shear layer at the base of the convection zone if one wants to study the solar global dynamo (Browning *et al.* 2006).

In Figure 2a,b, we represent the differential rotation profile of our latest hydrodynamic case including a stable layer and a tachocline of shear. This model is similar to the purely unstable case, except that we have extended the shell thickness such as to introduce a stable layer at the bottom part of the numerical domain and we have imposed both a viscous drag to obtain a uniform rotation below $r = 0.66R$ and a thermal wind forcing at $r = 0.68R$ to retain a strong solar like differential rotation profile in the convective layers. Indeed Miesch, Brun & Toomre (2006) showed that enforcing a thermal wind balance at the bottom BC of a 3-D purely hydrodynamical convective model, results on a model even closer to helioseismic inversion i.e. more radial at mid-latitude. More turbulent (non isotropic) heat transport in the convection zone or feed back from the tachocline could lead to such an enhanced baroclinic forcing. In this model the tachocline is rather broad ($\sim 0.1 - 0.15\,R$) compared to helioseismic inversions ($\leqslant 0.05\,R$) (Corbard *et al.* 1999), and so the associated thermal wind is not strong enough to enforce the conical profile of the differential rotation, we thus need to further enhance the thermal forcing.

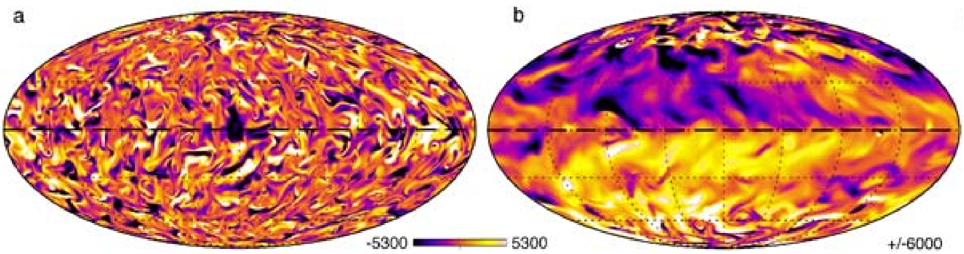

Figure 3. Snapshot using a Mollweide projection, of the longitudinal magnetic field near the top (left) and at the bottom of the domain (right) for the model with an imposed tachocline. Note how different the longitudinal field is in the convection zone (identical to what is shown in Figure 1) and in the tachocline, with a clear anti-symmetry with respect to the equator.

In Figure 2c we display an azimuthal average of the toroidal field. It is clear that in the stable zone there is a large organized prominent mean ($m = 0$) toroidal field whereas in the convection zone the field is small scale and much weaker. This is confirmed in Fig. 2d where we display horizontal average of the various components of ME, with TME becoming the stronger component below 0.7 R. In Figure 3 we represent Mollweide projections of the radial velocity near the surface and of the longitudinal field at two depths, near the surface and in the stable layer. It is striking how different B_ϕ is within the convective layer and in the stable zone, with a clear antisymmetry with respect to the equator of B_ϕ in the latter, whereas the non axisymmetric fields are mainly located in the convection as in Fig. 1. The organisation of the field is due to the radial shear present in the tachocline that wind up the field pumped down by the turbulent convective plumes. This simulation has been run for about 2500 days, and no reversal of the mean field has been observed. The presence of the strong organized mean field in the stable layer helps to stabilize the poloidal field in the convection zone, which fluctuates and undergoes much less irregular reversals compared to the purely unstable magnetized case. However the toroidal field in the tachocline has not yet undergone magnetic buoyancy instability (dynamo block d), since it is still relatively weak ($\sim 5000G$).

5. Prospect

We have seen that global scale simulations of solar convection and magnetism are making closer contact to observations, with the tachocline playing a major role in shaping the solar differential rotation and organizing the strong mean toroidal field. However our state-of-the-art simulations are still lacking an 11-year magnetic cycle, a butterfly diagram for the sunspot emergence and field propagation. Clearly the level of turbulence of our convection zone, the value of the magnetic Prandtl number at which we observed dynamo action, the stiffness of the stable layer and the thinness of a self consistently generated tachocline are properties that need to be improved in our future simulations.

Acknowledgements

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Discussion

A. Ingersoll: How do you interpret the entropy gradient and/or the tachocline that you imposed at the lower boundary ? It seems arbitrary to impose these conditions.

A.S. Brun: The tachocline is clearly observed in the Sun. Its dynamical and thermal influence on the solar convection zone is still question of debates, but it is reasonnable to think that this boundary has some influence. An easy way to model it is to assume that the tachocline is in thermal wind balance and thus imposed a latitudinal variation of the entropy.

F. Rincon: Does the inclusion of the tachocline make a difference for the growth rate of the dynamo ?

A.S. Brun: In the convection zone proper, no we have not seen any differences. However it is clear that the presence of an relatively strong mean toroidal and poloidal field in the the tachocline modify the temporal intermittency of the magnetic field observed in the convection zone. The field in the stable layer play a stabilizing role on the field continously generated in the convection zone, a bit like the magnetic field in the earth solid iron core stabilize the field in the earth liquid iron core surrounding it.