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Global models of the magnetic Sun

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Abstract. We briefly present recent simulations of the internal magnetism of the Sun with the 3-D ASH code and with the 2-D STELEM code. The intense magnetism of the Sun is linked to local and global dynamo action within our star. We focus our study on how magnetohydrodynamical processes in stable (radiative) or unstable (convective) zones, nonlinearly interact to establish the solar differential rotation, meridional circulation, confine the tachocline, amplify and organise magnetic fields and how magnetic flux emerge to the surface. We also test the robustness of flux transport dynamo models to various profiles of circulation.

Keywords. Sun: cycle, dynamo, rotation, convection, flux emergence, radiative interior; MHD

1. The Nonlinear Sun

The Sun's surface and hot atmosphere exhibits a wide range of magnetohydrodynamical processes. The magnetic fields, like the underlying turbulence, can be both orderly on some scales and chaotic on others. Most striking is that the Sun exhibits 22-year cycles of global magnetic activity, involving sunspot eruptions with very well defined rules for field parity and emergence latitudes as the cycle evolves. Coexisting with these large-scale ordered magnetic structures are small-scale but intense magnetic fluctuations that emerge over much of the solar surface, with little regard for the solar cycle.

The origin of the observed solar magnetic fields must rest with dynamo processes occurring deep within the star. Within the solar convection zone, complex interactions between compressible turbulence and rotation serve to redistribute angular momentum so that a strong differential rotation is achieved. Further, since the fluid is electrically conducting, currents will flow and magnetic fields must be built. Yet there are many fundamental puzzles about the dynamo action that yields the observed fields. The observed large diversity of magnetic phenomena must thus be linked to two conceptually different dynamos: a large-scale/cyclic dynamo and a turbulent small scale one (e.g., Cattaneo & Hughes 2001; Ossendrijver 2003). It is currently believed that the tachocline (Spiegel & Zahn 2002) plays a crucial role in the operation of the large scale dynamo and also possibly influences the profile of the solar differential rotation. Further hydrodynamical and MHD instabilities seem to play an important role in the dynamical evolution of the inner radiative interior with here also a likely feed back on the surface layers. In Fig 1 we present a schematic view that illustrates the key elements thought to be at the origin of the observed solar dynamical and magnetic phenomena. In the following sections we briefly present recent numerical studies of some of these ingredients.

1.1. *Convection and Large-scale flows*

Convection is central to the understanding of the complex solar dynamics. We have published a series of papers (Brun & Toomre 2002 (BT02), Miesch, Brun & Toomre 2006 (MBT06), Miesch *et al.* 2008) that study with high resolution numerical simulations the establishment of turbulent convection in a rotating spherical shell and the associated

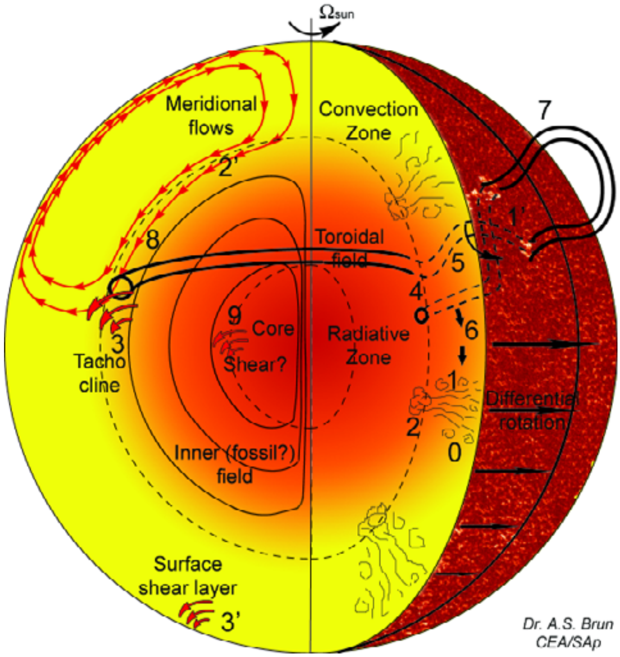

Figure 1. Theoretical schematic of the solar inner magnetism and dynamo: 0: Turbulent convection (plumes); 1: Generation/self-induction of B ("α-effect") or 1': Tilt of active region (source of B poloidal); 2: Turbulent pumping of B ("β-effect") in tachocline or 2': Transport of B by meridional flows from CZ into the tachocline; 3: Field ordering in toroidal structures by large scale shear in the tachocline ("ω-effect"); 3': Solar sub surface weather (SSW), surface dynamics of sunspot?; 4: Toroidal field subject to m=1 or 2 MHD instabilities; 5: Rise (lift) + rotation (tilt) of twisted toroidal structures; 6: Recycling of weak field in CZ or; 7: Emergence of bipolar structures at the surface; 8: Interaction between dynamo induced field, inner (fossil?) field, in the tachocline (with shear, turbulence, waves); 9: Instability of inner field (stable configuration?) + shearing via ω-effect at nuclear core edge? Is there a dynamo loop realized in RZ?

mean flows. The convective patterns are found to be highly time dependent and to possess a large spectrum of spatial and temporal scales. The radial velocity is dominated by narrow cool downflow lanes and broad warm upflows, with a more isotropic behaviour at higher latitudes, even though this trend seems to be less present in the most turbulent case (Miesch *et al.* 2008). Characteristic spatial scale here are larger than supergranulation, which is as of today, the smallest convective scale that such global models can simulate. The temperature fluctuations exhibit a banded appearance most likely linked to an inner thermal wind, that contributes somewhat to the establishment of the differential rotation (see below). The strongest vortices are well correlated with the coldest fluctuations resulting in an outward transport of heat.

Helioseismic inversions of large-scale, axisymmetric, time-averaged flows in the Sun (Thompson *et al.* 2003) currently provide the most important observational constraints on global-scale models of solar convection (BT02, MBT06, Miesch *et al.* 2008). Of particular importance and reasonably well constrained by helioseismology, is the mean longitudinal flow, i.e. the differential rotation $\Omega(r, \theta)$, which is characterised by a fast equator, slow poles and a profile almost independent of radius at mid latitudes. In most of our recent simulations a fast equator, a monotonic decrease of Ω with latitude and some constancy along radial line at mid latitudes are established, all these attributes being in reasonable agreement with helioseismic inferences. A study of the redistribution of angular momentum in our convective shells reveals that Reynolds stresses are at the origin of the equatorial acceleration opposed mainly by meridional circulation (BT02, Miesch *et al.* 2008). The relative importance of the Reynolds stresses and the thermal wind which is linked to baroclinic effects in establishing the solar differential rotation is still a subject of debate. In our 3–D simulations (MBT06) we do find that the thermal wind account for a fraction of the differential rotation profile in the bulk of the convection zone, but there are many locations, mainly close to high shearing regions, where it does not. In our simulations, convection redistribute heat and angular momentum both in radius and latitude and establish latitudinal gradients of temperature and entropy compatible with a differential rotation. By enforcing a thermal wind at the bottom BC of a 3-D purely hydrodynamical convective model, MBT06, confirmed that the solar differential rotation could be influenced by baroclinic or thermal forcing at the base of the convection zone by being more radial at mid-latitude. The exact nature of this thermal balance due either to the influence of the tachocline or to turbulent latitudinal heat transport or both effects, still need to be modelled in greater details. The near constancy of the isocontours of Ω along radial lines could be used in turn to assess the radial structure of the tachocline if this boundary layer is assumed to be in strict thermal wind balance (see Brun 2007a).

1.2. *Magnetised Convection and Dynamo Action*

By including a weak seed magnetic field in our simulation of turbulent convection, we can study in detail the nonlinear interactions between turbulence, rotation and magnetic fields. We find that the magnetic energy (ME) grows by many order of magnitude through dynamo action if the magnetic Reynolds number ($Rm = vL/\eta$) of the flow is above a critical value (see Brun *et al.* 2004 (BMT04)). Following the linear phase of exponential growth, ME saturates, due to the nonlinear feed back of the Lorentz forces, to a fraction value of the kinetic energy (KE) and retains that level over many Ohmic decay times. Upon saturation, KE has been reduced significantly when compared to its initial purely hydrodynamical value. This variation is mostly due to a reduction of the energy contained in the differential rotation. The energy contained in the convective motions is less influenced, which implies an increased contribution of the non-axisymmetric motions to the total kinetic energy balance.

The radial magnetic field is found to be concentrated in the cold downflow lanes, with both polarities coexisting having been swept there by the horizontal diverging motions at the top of the domain. The Lorentz forces in such localised regions have a noticeable 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. The magnetic field and the radial velocity possess a high level intermittency both in time and space, revealed by extended wings in their probability distribution functions and are quite asymmetric (BMT04). Fast reversal of the poloidal field are observed ($\sim$ 400 days) which are typical of a dynamical system but disagree with the observed 11-yr cycle. In an attempt to resolve that issue we have recently included a stably stratified tachocline of shear in our magnetic simulations (Browning *et al.* 2006). We confirm through nonlinear simulations that it plays a crucial role in organising the irregular field produced by the convection zone into intense axisymmetric toroidal structures. The presence of this large scale mean field does seem to influence the nonlinear behaviour of the simulations leading to much less frequent if any magnetic field reversals or excursions.

With fairly strong magnetic fields sustained in our magnetic simulations, it is to be expected that the differential rotation Ω established in the purely hydrodynamical case will respond to the feedback from the Lorentz forces. Indeed we found that the main effect of the Lorentz forces is to extract energy from the differential rotation as the weakening of KE indicates. A careful study of the redistribution of the angular momentum in the 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 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 a tachocline of shear.

In order to study the ingredients necessary at establishing a 22-yr cycle we have developed a mean field solar dynamo model of flux transport type using a Babcock-Leighton (BL) source term (Charbonneau 2005, Dikpati *et al.* 2004, Jouve & Brun 2007a). In this model, the meridional circulation transports the poloidal field from the surface, where it contributes to the twisted nature of the solar active regions, to the bottom of the convection zone where it is transformed into toroidal field in the tachocline. This meridional circulation thus plays a major role in the behaviour of BL flux transport dynamo models. Inspired by recent observations and 3-D simulations that both exhibit highly variable multicellular flows in the solar convective zone, we seek to characterise the influence of such flows on the behaviour of dynamo models (Jouve & Brun 2007a, Jouve *et al.* 2008). We have tested several types of meridional flows: 1 large single cell, 2 cells in radius and 4 cells per hemisphere. We confirm that adding cells in latitude tends to speed up the dynamo cycle whereas adding cells in radius more than triples the period. Our studies show that adding cells in radius or in latitude seems to favour the parity switching to a quadrupolar solution. According to our numerical models, the observed 22-yr cycle and dipolar parity is easily reproduced by these models, but the butterfly diagram and phase relationship between the toroidal and poloidal fields are affected to a point where it is unlikely that such multicellular flows persist for a long period of time inside the Sun, unless of course another solar dynamo model is considered. Chan *et al.* (2007) has recently developed a 3-D interface dynamo model with the purpose of studying the 11-yr cycle.

1.3. *Radiative Zone and the Tachocline*

We now turn to considering the magnetohydrodynamical processes acting in the solar radiative interior and in the tachocline inspired by the work of Gough & McIntyre (1998), i.e a latitudinal shear is imposed on top of a stable radiative zone, and we expect a fossil dipolar magnetic field to prevent that shear for propagating inward. Other processes such as anisotropic turbulence in the overshooting layer could also be invoked (see Spiegel & Zahn 1992). Two important hypothesis of our work are that we let the poloidal field diffuse, and that the tachocline circulations are driven mainly by thermal (not viscous) diffusion, as in the Sun (see Brun & Zahn 2006 (BZ06)). Moreover, we resolve the Alfvén crossing time; this enables us to describe non-axisymmetric MHD instabilities which may lead to drastic reconfigurations of the magnetic field (Spruit 2002, Braithwaite & Spruit 2004, Zahn, Brun & Mathis 2007 (ZBM07), Brun 2007b), following the pioneering work of Tayler (Tayler 1973 and collaborators).

In BZ06 we have studied several magnetic field configurations in the solar radiative interior in order to assess if the shear of the tachocline will or will not spread inward and reach a thickness much larger than inverted by helioseismic technics (i.e $h < 0.05R$). We actually find that the field always connect to the shear, and that burying it just delay in time the reconnection. When the field lines make contact with the shear, we notice a fast increase of the mean toroidal energy in a thin latitudinal band, which corresponds to the magnetopause anticipated by Gough & McIntyre. However the existence of this magnetic layer does not prevent the field lines to connect to the imposed latitudinal shear, and to establish in an Alfvenic time scale a differential rotation in the radiative interior. Since this is not observed (inverted) in the Sun, this scenario of the magnetic confinement of the tachocline seems in difficulty. An interesting result found by the nonlinear calculations of BZ06 and confirmed in ZBM07 and Brun 2007b, is that it is unlikely that inside the radiative zone of the Sun the magnetic field topology is as simple as a pure dipole. It is most likely in a mixed poloidal-toroidal configuration (as anticipated with a linear approach by Tayler 1973), with the two components of the field being roughly of the same amplitude. How this inner field interact with the dynamo field generated in the convection zone and stored in the tachocline and could such an inner field sustains a dynamo on its own through Tayler's instability, as suggested by Spruit 2002, are very interesting question that we have started to tackle recently (see ZBM07).

1.4. *Flux Emergence*

Active regions on the solar surface are believed to take their origin from strong toroidal fields created in the tachocline. We thus need to understand the rising mechanisms of strong toroidal structures through the CZ. Many models carried out since the 80's (see Fan 2004 for a recent review) relied on the assumption that toroidal flux is organised in the form of discrete flux tubes that will rise cohesively from the base of the CZ up to the solar surface (see Cattaneo *et al.* 2006 for a less idealised view of a flux tube). We have again used the ASH code to study the 3-D evolution of buoyant magnetic flux ropes both in an adiabatically stratified spherical shell (Jouve & Brun 2007b) and in a fully developed convection (Jouve & Brun 2008 in prep.). In the isentropic case, we confirm that the twist of the field lines reduces the generation of vorticity (Emonet & Moreno-Insertis 1998) and that the tube is deviated from the radial direction by the magnetic curvature force (Spruit & van Ballegooijen 1982) especially when the tube is introduced at high latitudes. Moreover, we can show that rotation reduces the efficiency of the buoyancy force, leading the flux ropes to rise less rapidly in a rotating background. In the fully convective case, another major parameter has to be taken into account: the initial magnetic field strength inside the tube. In sufficiently weak B cases, downflows and upflows control the rising velocity of particular regions of the rope and could in principle favour the emergence of flux through Ω-loop structures. In these cases, meridional flows also determine the trajectory of the tube when it reaches the top of the domain. Future improvement will involve the introduction of a stable atmosphere on top of the CZ.

2. Conclusions

We have shown that numerical simulations of the complex internal solar magnetohydrodynamics are becoming more and more tractable with today's supercomputers. In particular we have studied how turbulent convection under the influence of rotation can establish a strong differential rotation and weak meridional circulation, generate magnetic fields through dynamo action and how Lorentz forces act to diminish the differential rotation by having Maxwell stresses transporting angular momentum poleward and thus opposing the Reynolds stresses (see BT02, BMT04, MBT06). Many challenges remain, among them the understanding of the two shear layers present at the base (the tachocline) and at the top of the solar convection zone, or magnetic coupling to the solar atmosphere (see reviews e.g. Erdélyi 2006a,b) is a priority since these layers are directly linked to the solar dynamo and subsurface weather (Haber *et al.* 2002). Another challenge is to get a more accurate and deeper inversion of the meridional circulation present in the solar convection since it plays a crucial role in current mean field solar dynamo models (Dikpati *et al.* 2004, Jouve & Brun 2007a). Another key element of the solar dynamo is the emergence of magnetic flux from deep within the Sun up to its surface. The first 3-D MHD simulations in a spherical shell have been performed (Jouve & Brun 2007b). They show that the strength, the topology and the latitude of the flux tube all influence its nonlinear evolution. In order to progress in our understanding of the deep solar interior, we have started to study with ASH in three dimensions, the solar tachocline and radiative zone (BZ06, ZBM07). We have considered how a dipolar magnetic field could oppose the radiative spread of the tachocline. We have found that independently of the degree of confinement of the fossil magnetic field it will diffuse into the convection zone and communicate to the radiative interior, first, at high, then at lower latitudes, the differential rotation, therefore enforcing an isorotation of Ω along the poloidal field lines. This behaviour is known as Ferraro's law of isorotation. Work is in progress to compute with ASH in one single global model the solar convection and radiation zones.

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