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Dynamo action in simulations of penetrative solar convection with an imposed tachocline

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We summarize new and continuing three-dimensional spherical shell simulations of dynamo action by convection allowed to penetrate downward into a tachocline of rotational shear. The inclusion of an imposed tachocline allows us to examine several processes believed to be essential in the operation of the global solar dynamo, including differential rotation, magnetic pumping, and the stretching and organization of fields within the tachocline. In the stably stratified core, our simulations reveal that strong axisymmetric magnetic fields (of ~ 3000 G strength) can be built, and that those fields generally exhibit a striking antisymmetric parity, with fields in the northern hemisphere largely of opposite polarity to those in the southern hemisphere. In the convection zone above, fluctuating fields dominate over weaker mean fields. New calculations indicate that the tendency toward toroidal fields of antisymmetric parity is relatively insensitive to initial magnetic field configurations; they also reveal that on decade-long timescales, the magnetic fields can briefly enter (and subsequently emerge from) states of symmetric parity. We have not yet observed any overall reversals of the field polarity, nor systematic latitudinal propagation.

1 Challenges of solar magnetism

How the Sun generates cyclical magnetic fields is an enduring mystery. Observed orderly patterns of field emergence and evolution at the solar surface – including, most strikingly, periodic global polarity reversals and equatorward propagation of sunspots – point to the existence of a global dynamo that can amplify and organize magnetic fields. In recent years, new insights into how the dynamo may operate have come from helioseismology, which probes the solar interior using some of the 10^7 acoustic oscillation modes that ring within the Sun (e.g., Gough & Toomre 1991). In particular, the helioseismically inferred region of strong shear at the base of the convection zone, called the tachocline (Spiegel & Zahn 1992), was not anticipated but is now widely thought to play a major role in the operation of the solar dynamo.

Indeed, for the past decade, the most broadly accepted paradigm for explaining the origins of solar magnetism has been the "interface dynamo" (Parker 1993; review in Ossendrijver 2003). This model proposes that the generation of fields is largely accomplished in several conceptually distinct stages occurring in different locations within the Sun. Poloidal fields are thought to be generated from toroidal ones within the convection zone (the α-effect), either by the cumulative action of cyclonic convection (Parker 1955; Steenbeck, Krause & Rädler 1966) or by the shredding of active regions near the surface (Babcock 1961; Leighton 1969). These poloidal fields are transported downwards into the tachocline of rotational shear (the β-effect), where they are stretched and amplified by differential rotation to yield strong toroidal fields (the ω-effect). These fields may then experience instabilities and rise due to magnetic buoyancy, with some fraction of the field later appearing at the surface and the rest being recycled as part of the dynamo cycle.

No nonlinear 3-D simulation has yet succeeded in incorporating all these effects into a global model of the solar dynamo. Many of these dynamo "building blocks" have, however, been studied individually, using simulations that encompassed limited spatial domains. For instance, numerous simulations of convection in Cartesian boxes have examined small-scale dynamo action (e.g., Cattaneo 1999) and pumping of magnetic fields downwards into stably stratified regions (e.g., Tobias et al. 2001). Global nonlinear simulations in a spherical shell geometry have examined the building of differential rotation by turbulent convection (e.g., Miesch, Brun & Toomre 2006) and dynamo action amidst that convection (Brun, Miesch & Toomre 2004), but until recently had not included the coupling of the magnetized convection zone to a stably stratified tachocline.

In this paper, we report briefly on the the first global simulations in a spherical geometry to consider dynamo action by turbulent convection that can penetrate downward into

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a sheared stably stratified region. Because the stretching of toroidal fields by shear within the tachocline is thought to play a key role in the global solar dynamo, we have essentially imposed such shear within the stable layer (in a manner described in Sect. 2). We presented the first results from these simulations elsewhere (Browning et al. 2006); here, we provide an update on the further evolution of the models described in that Letter. We also report on follow-up simulations designed to assess the robustness of some of the findings of Browning et al. (2006). We briefly describe our numerical model in Sect. 2 below, report on the main results of our simulations in Sect. 3, and comment on their significance in Sect. 4.

2 Model formulation

Our simulations are highly simplified models of the bulk of the solar convection zone and a portion of the underlying stable region. The spherical computational domain extends from 0.62 to 0.94 $R_\odot$. The frame rotates at the solar angular velocity $\Omega_\odot = 2.6 \times 10^{-6}$ s^{-1}. The initial stratifications of density, temperature, and pressure are consistent with a 1-D stellar model; however, we have softened the steep entropy gradient encountered in going from the convection zone to the subadiabatic layer below, in order to ease numerical resolution of the internal gravity waves produced there by overshooting plumes (e.g., Miesch et al. 2000).

We employ the pseudospectral anelastic spherical harmonic code ASH for our modeling (see Clune et al. 1999; Brun, Miesch & Toomre 2004). ASH solves the 3-D MHD equations in the anelastic approximation, using an LES-SGS approach in which the largest spatial scales are explicitly resolved, while smaller scales are modeled using a sub-grid-scale (SGS) treatment. Here, those small scales of turbulence are manifested simply as enhancements to the viscosity ν, thermal diffusivity κ, and magnetic diffusivity η, which are thus effective eddy viscosities and diffusivities.

In the Sun, the tachocline of shear is believed to play a central role in the global dynamo (e.g., Ossendrijver 2003; see Brandenburg 2005 for a contrary view). The origins of this boundary layer are still uncertain, with internal gravity waves, anisotropic turbulent processes, and magnetic stresses all advocated as potential players in its creation (see review in Miesch 2005). Some of these processes may equilibrate only over very long timescales (e.g., Gough & McIntyre 1998), which the limited duration of our simulations cannot capture. Furthermore, in our simulations the viscosities and diffusivities are larger than in the actual solar interior and the overshooting region is more extended; both of these effects tend to exaggerate the coupling between the convective and radiative zones. Spontaneous realization of a narrow tachocline in our simulations would thus be unlikely at this stage.

We have therefore sought to impose a tachocline of shear in two complementary ways. Firstly, we apply a hydrodynamical drag force to motions in the stable layer; the functional form of this drag force is taken to be a hyperbolic tangent centered near the bottom of the convection zone, so that motions within the bulk of the convective envelope are unimpeded. Without such forcing, any differential rotation established self-consistently within the convective envelope would rapidly imprint itself upon the radiative zone through viscous and thermal diffusion. Secondly, we have imposed a small entropy variation near the core-envelope interface in order to emulate the possible coupling of the convective and stable regions through thermal wind balance in the tachocline (as discussed in Miesch, Brun & Toomre 2006). This thermal forcing represents an effective way to maintain strong latitudinal differential rotation in the convection zone, in the face of the residual drag force that is transmitted to that zone by diffusion.

We assume impenetratable, stress-free boundaries. The magnetic field is matched to a potential field at the top surface and to a perfectly conducting lower boundary. We employ horizontal resolution of $N_\theta = 512$, $N_\phi = 1024$, and adopt a stacked Chebyshev expansion (with $N_r = 98$) in the radial direction. The Prandtl number $\mathrm{Pr} = \nu/\kappa$ and magnetic Prandtl number $\mathrm{Pm} = \nu/\eta$ are fixed at $\mathrm{Pr} = 0.25$ and $\mathrm{Pm} = 8$, respectively. In the Sun, the Pm based on microscopic viscosity and diffusivity is much less than unity. Taking $\mathrm{Pm} > 1$ allows us to achieve fairly high magnetic Reynolds numbers Rm, and sustained dynamo action, at modest numerical resolution; at lower Pm, the critical Rm needed for dynamo action may increase considerably (Boldyrev & Cattaneo 2004; Shekochihin et al. 2005). The field strengths and morphology are likely sensitive at some level to the Pm chosen.

The MHD simulation of Browning et al. (2006), which we here denote as case A, was begun by introducing a small seed toroidal magnetic field into a hydrodynamic progenitor. The seed field was toroidal and axisymmetric ($m = 0$), confined to the convection zone, and contained both symmetric and antisymmetric (even and odd ℓ) components. Because one of the striking results of that paper was the antisymmetric parity exhibited by the evolved toroidal magnetic fields, we conducted a follow-up case B with somewhat different initial conditions. For this simulation, the seed toroidal field was purely symmetric about the equator, and consisted of high-ℓ, high-m (non-axisymmetric) modes.

3 Dynamo action yields organized magnetism

Within the convective envelope, the flows are intricate and highly time-dependent. Fast, narrow downflows contrast with broader, weaker upflows, as is typical in compressible convection (e.g., Brummell et al. 2002). Some coherent downflow lanes persist for extended intervals, and have a significant influence on angular momentum redistribution in the convection zone. Many downflow plumes extend downward and overshoot into the radiative interior, where buoyancy braking eventually brings them to a halt.

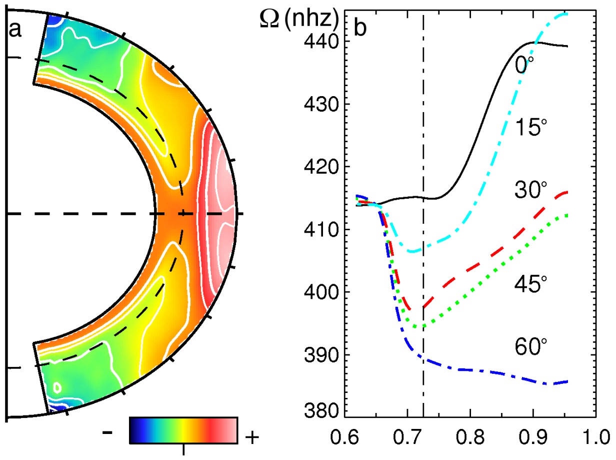

Fig. 1 (online colour at: www.an-journal.org) Angular velocity Ω in case A averaged in time and in longitude, shown (*a*) as a contour plot in radius and latitude and (*b*) as a function of radius along indicated latitudinal cuts.

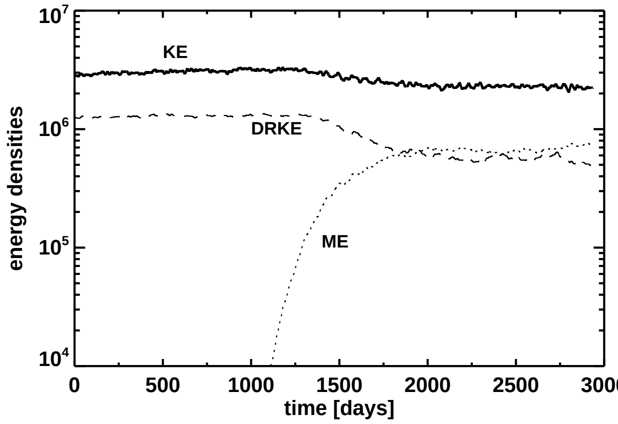

Fig. 2 Temporal evolution of kinetic and magnetic energy densities in case B. Shown are the volume-averaged magnetic energy density (ME), the total kinetic energy (KE), and the kinetic energy in differential rotation (DRKE), all relative to the rotating frame.

The convection establishes strong differential rotation. Figure 1 shows the mean angular velocity $\hat{\Omega}$ in case A as a contour plot in radius and latitude (Fig. 1a), together with its variation with radius along selected latitudinal cuts (Fig. 1b). There is a prominent decrease in $\hat{\Omega}$ from equator to pole within the convection zone. The angular velocity contrast between equator and 60°is about 55 nHz near the upper boundary, or 15% of the frame rotation rate. This angular velocity contrast is smaller than that realized in simulations that did not allow penetration into a stable layer (e.g., Miesch et al. 2006), and Ω is more constant on cylinders aligned with the rotation axis. Below the convection zone, there is a rapid transition to uniform rotation, in keeping with our application of a hydrodynamic drag force there. The overall fast equator and slow pole behavior is reminiscent of the interior angular velocity profiles deduced from helioseismology (e.g., Thompson et al. 2003), but the simulation possesses more radial shear within the convection zone than does the Sun. Nonetheless, a region of strong shear akin to the solar tachocline has clearly been established.

The flows in cases A and B act as effective magnetic dynamos, amplifying the seed magnetic fields by many orders of magnitude and sustaining them against Ohmic decay. The growth of the magnetic energy in case B, and its equilibration at about 30% of the total kinetic energy, are shown in Fig. 2. The equilibrated magnetic fields in case B do not differ appreciably from those of case A reported in Browning et al. (2006). Within the bulk of the convection zone, strong fluctuating (non-axisymmetric) magnetic fields, with rms strengths ~ 3000 G, are accompanied by comparatively weak mean (axisymmetric) fields which have time-averaged strengths of less than about 300 G. The magnetic fields in the convection zone exhibit no evident polarity preferences, with fields of both polarities found intermixed in the northern and southern hemispheres. Complex and intermittent magnetic field structures on many spatial scales appear and evolve, partly tracing the intricate convective flows.

In the underlying stable region, Fig. 3a reveals that the magnetic field has been strikingly organized. The longitudinal field there has been stretched by the shear into large-scale toroidal structures that extend around much of the domain. The toroidal field possesses a clear antisymmetric parity, with fields in the northern hemisphere largely of opposite sign to those in the southern hemisphere. Another assessment of the organized nature of the toroidal fields is provided by the time-averaged axisymmetric B_ϕ displayed in Fig. 3b. The opposite polarities of fields in the two hemispheres are evident; so, too, is the greater strength of mean toroidal fields in the stable layer relative to those in the convection zone. Indeed, mean fields of about 3000 G in strength are realized in the radiative region, in contrast to the tenfold weaker mean fields in the convective envelope.

The organization of magnetic fields in the stable layer into predominantly large-scale structures, and the antisymmetric parity of the toroidal field, both appear to be long-lived effects. In Browning et al. (2006), we reported that the antisymmetric parity in case A had persisted for as long as we continued our simulations. Further evolution of that case (extending for a total of about 17 years) has revealed one transition to a state of symmetric parity, in which the strong negative toroidal field in the northern hemisphere (Fig. 3a,b) was replaced by a somewhat weaker positive-polarity field. The instantaneous axisymmetric toroidal field during this interval of symmetry is shown in Fig. 3c This predominantly symmetric state lasted only for a brief interval ($<$ 200 days), after which strong negative toroidal fields were reestablished in the northern hemisphere. The brief transition to a symmetric state, and subsequent emergence from it, occurred approximately 12 years after the equilibration of magnetic energy in case A. Our companion case B was designed partly to test whether the antisymmetric parity of

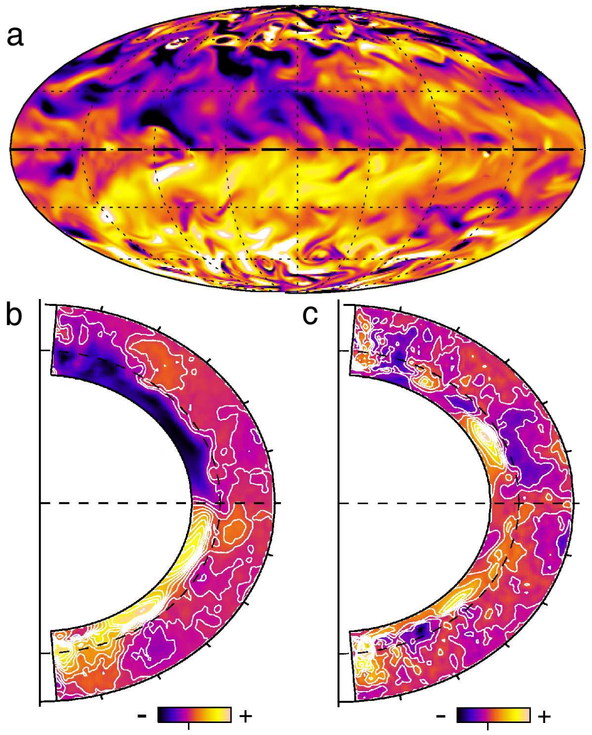

Fig. 3 (online colour at: www.an-journal.org) Toroidal magnetic fields established in the stable layer and the convective envelope in case A. (a) Mollweide projection showing an instantaneous view of B_ϕ on a spherical surface within the radiative region (at $r = 0.67$ R$_\odot$). (b–c) Contours in radius and latitude of B_ϕ averaged in time and in longitude, sampling (b) the predominant antisymmetric parity and (c) a short (150-day) interval during which the toroidal field was much more symmetric.

the toroidal field was partially an artifact of the initial magnetic field conditions, which contained some antisymmetric components. Evolution of case B for approximately 10 years has shown that antisymmetric $m = 0$ toroidal fields are established even when the initial toroidal field was both purely symmetric about the equator and non-axisymmetric ($m \neq 0$). The equilibrated magnetic fields through most of the evolution of case B appear essentially identical to those of Fig. 3a,b. In neither simulation have we observed overall polarity reversals or systematic latitudinal field propagation.

4 Summary and reflections

The combined actions of convection and an imposed tachocline have, in our simulations, yielded magnetic fields that possess some striking properties. The strong mean toroidal fields realized in the stably stratified layer, the generally antisymmetric parity displayed by those fields, and the decade-long time spans over which one overall field polarity dominates, are all reminiscent of the organized magnetism observed at the solar surface in sunspots. Conversely, the lack of field reversals or systematic latitudinal propagation represents a significant departure from those same surface observations. The origins of these features are not yet clear, but we have commented elsewhere (Browning et al. 2006) on some of the most likely contributing processes. The presence of shear and a stable layer likely figure prominently in setting the field strength and morphology; more concentrated shear, as realized in a narrower tachocline, might well yield even greater mean field strengths than reported here.

The similar evolved magnetism realized in the two cases A and B suggest that these field properties are relatively insensitive to the initial magnetic field conditions adopted. The new case B had a purely symmetric initial toroidal field, yet ultimately exhibits predominantly antisymmetric fields like those that typically prevail in case A. On the other hand, our further evolution of case A (from Browning et al. 2006) indicates that the preference for dipolar symmetry is not absolute: on decade-long timescales, that simulation has transitioned into and out of quadrupolar (symmetric) states as well. Further work will be required to determine what controls these transitions between symmetric and antisymmetric modes, and similarly to test the robustness of the other features reported here.

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References

Babcock, H.W.: 1961, ApJ 133, 572
Boldyrev, S., Cattaneo, F.: 2004, PhRvL 92, 144501
Brandenburg, A.: 2005, ApJ 625, 539
Browning, M.K., Miesch, M.S., Brun, A.S., Toomre, J.: 2006, ApJ 648, L157
Brummell, N.H., Clune, T.L., Toomre, J.: 2002, ApJ 570, 825
Brun, A.S., Miesch, M.S., Toomre, J.: 2004, ApJ 614, 1073
Cattaneo, F.: 1999, ApJ 515, L39
Clune, T.L., Elliott, J.R., Glatzmaier, G.A., Miesch, M.S., Toomre, J.: 1999, ParC 25, 361
Gough., D.O., Toomre, J.: 1991, ARA&A 353, 678
Gough., D.O., McIntyre, M.E.: 1998, Nature 394, 755
Leighton, R.B.: 1969, ApJ 156, 1
Miesch, M.S., Elliott, J.R., Toomre, J., Clune, T.L., Glatzmaier, G.A., Gilman, P.A.: 2000, ApJ 532, 593
Miesch, M.S.: 2005, LRSP 2, 1
Miesch, M.S., Brun, A.S., Toomre, J.: 2006, ApJ 641, 618
Ossendrijver, M.: 2003, A&ARv 11, 287
Parker, E.N.: 1955, ApJ 122, 293
Parker, E.N.: 1993, ApJ 408, 707
Schekochihin, A.A., Haugen, N.E.L., Brandenburg, A., Cowley S.C., Maron, J.L., McWilliams, J.C.: 2005, ApJ 625, L115
Spiegel, E.A., Zahn, J.-P.: 1992, A&A 265, 106
Steenbeck, M., Krause, F., Rädler, K.-H.: 1966, ZNatA 21, 369
Thompson, M.J., Christensen-Dalsgaard, J., Miesch, M.S., Toomre, J.: 2003, ARA&A 41, 599
Tobias, S.M., Brummell, N.H., Clune, T.L., Toomre, J.: 2001, ApJ 549, 1183