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Spherical shell studies of differential rotation and magnetic dynamo action in the solar convection zone

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The solar global dynamo responsible for the observed 22-year cycles of magnetic activity is likely to require several dynamical processes operating at differing sites within the convection zone and below its base. The key elements within such an 'interface dynamo' involve (a) the generation of magnetic fields by the intense turbulence influenced by rotation within the deep solar convection zone, (b) the transport or pumping of these fields downward into the tachocline of shear at the base of this zone, (c) the stretching of fields there by differential rotation to form strong toroidal fields, and (d) the magnetic buoyancy instability of such structures leading to field loops ascending toward the surface. Fully self-consistent MHD simulations of the complete solar global dynamo are not yet feasible, given the vast range of dynamical scales involved in these turbulent processes. We have been studying many of these elements individually through three-dimensional numerical simulations of MHD convection within rotating spherical shells using our anelastic spherical harmonic (ASH) code on massively parallel supercomputers. In turning to element (a), we first considered in Brun, Miesch & Toomre (2004) the manner in which turbulent compressible convection within the bulk of the solar convection zone can generate large-scale magnetic fields through dynamo action. Since differential rotation is a key ingredient in all dynamo models, we also examined the nature of the rotation profiles that can be sustained within the deep convection zone as strong magnetic fields are built and maintained. We find that the convection is able to maintain a solar-like angular velocity profile despite the influence of Maxwell stresses which tend to oppose Reynolds stresses and thus reduce the latitudinal angular velocity contrast throughout the convection zone. The dynamo-generated magnetic fields exhibit a complex structure and evolution. Fluctuating magnetic fields with strengths of order 5000 G are realized that possess complex structures, with radial fields concentrated in downflow lanes and toroidal fields appearing as twisted ribbons extended in longitude. However, the associated mean fields are relatively weak and do not exhibit the systematic latitudinal propagation or periodic polarity reversals seen in the Sun.

We have most recently also incorporated elements (b) and (c) into global simulations of dynamo action achieved by turbulent convection able to penetrate downward into a tachocline of rotational shear (Browning, Miesch, Brun & Toomre 2006). We have achieved a tachocline by introducing a drag force upon the axisymmetric velocities (relative to our rotational frame) to force them to vanish smoothly near the base of the computational domain. Without this forcing, the differential rotation established self-consistently within the convection zone would imprint itself upon the radiative zone through viscous and thermal diffusion. Further, we impose within the overshooting region a weak latitudinal entropy variation in order to emulate the coupling between the convective envelope and the radiative interior through thermal wind balance within the solar tachocline, as evaluated by Miesch, Brun & Toomre (2006). The simulations reveal that strong axisymmetric toroidal magnetic fields (about 3000 G in strength) are realized within the lower stable layer, unlike in the convection zone where fluctuating fields are predominant. The toroidal fields in the stable layer possess a striking persistent antisymmetric parity, with fields in the northern hemisphere largely of opposite polarity to those in the southern hemisphere. The associated mean poloidal magnetic fields there have a clear dipolar geometry, but we have not yet observed any distinctive reversals or latitudinal propagation. The presence of these deep magnetic fields appears to stabilize the sense of mean fields produced by vigorous dynamo action in the bulk of the convection zone. The significant toroidal fields realized beneath the convection zone, the antisymmetric parity displayed by those fields, and the persistence of a single polarity for multiple years, are reminiscent of the highly organized magnetism that appears as sunspots at the solar surface. Further work is required to test the robustness of these features, and has been initiated as we expand upon the dynamical elements included in our efforts to model the solar global dynamo.

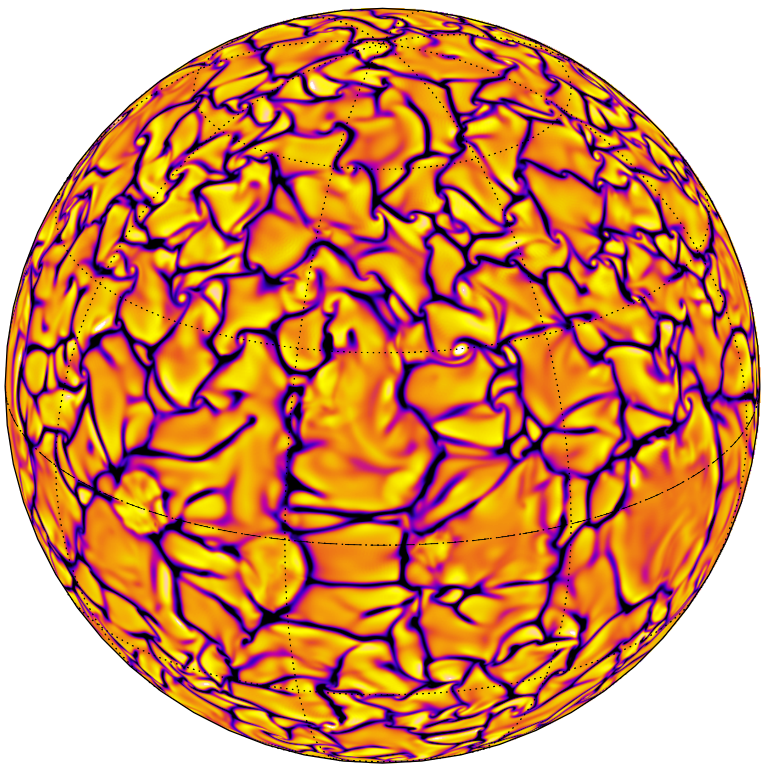

Figure 1: *Radial velocity snapshot of turbulent solar convection being studied with ASH, considering flows near the top of the computational domain. The downflows are shown in dark tones. The spherical harmonics being used to represent the horizontal structure extend to degree 680 in such modelling.*

References

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