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Global solar dynamo models: application to cyclic photospheric and nearly steady interior fields

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The most successful mean-field solar dynamo model is the so-called flux-transport dynamo, which operates with solar-like differential rotation, meridional circulation and α-effect. The Figure below (adopted from [5]) describes how this class of dynamo model works to produce a solar cycle.

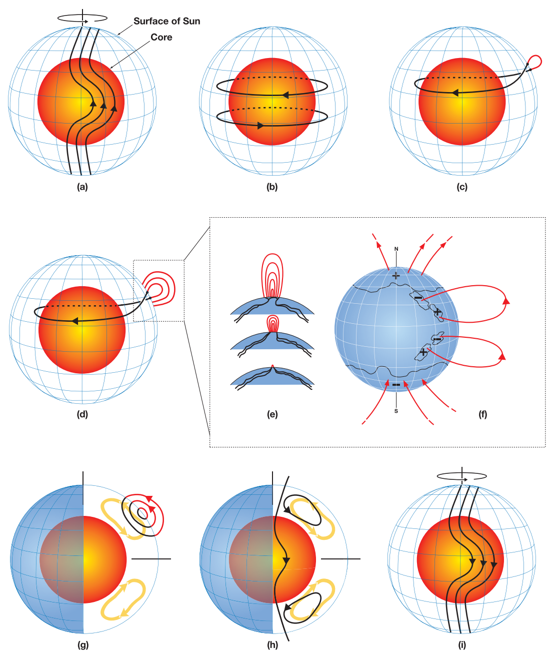

Figure 1: *Schematic of solar flux-transport dynamo processes. Red inner sphere represents the Sun's radiative core and blue mesh the solar surface. In between is the solar convection zone where dynamo resides. (a) Shearing of poloidal field by the Sun's differential rotation near convection zone bottom. The Sun rotates faster at the equator than the pole. (b) Toroidal field produced due to this shearing by differential rotation. (c) When toroidal field is strong enough, buoyant loops rise to the surface, twisting as they rise due to rotational influence. Sunspots (two black dots) are formed from these loops. (d,e,f) Additional flux emerges (d,e) and spreads (f) in latitude and longitude from decaying spots (as described in figure 5 of [1]). (g) Meridional flow (yellow circulation with arrows) carries surface magnetic flux poleward, causing polar fields to reverse. (h) Some of this flux is then transported downward to the bottom and towards the equator. These poloidal fields have sign opposite to those at the beginning of the sequence, in frame (a). (i) This reversed poloidal flux is then sheared again near the bottom by the differential rotation to produce the new toroidal field opposite in sign to that shown in (b).*

In applying flux-transport dynamos to the Sun, we constrain the flow fields by helioseismic measurements. We constrain the least-known ingredient, the diffusivity, by calibrating the model-output with observed magnetic features. We discuss in this talk recent applications of flux-transport dynamos that yield the following major results: (i) a pure interface dynamo without meridional circulation does not work for the Sun; (ii) a cyclic dynamo could be the origin of strong fields in the Sun's radiative core; (iii) large-scale mean solar cycle features can be predicted.

(i) We [2] show that a pure interface type dynamo will not work for the Sun if the skin effect for poloidal fields does not allow them to penetrate the tachocline. In the absence of tachocline radial shear participating in the dynamo process, a latitudinal differential rotation can provide the necessary Ω-effect to drive an oscillation in an interface dynamo, but it alone cannot produce the latitudinal migration and therefore a reasonable butterfly diagram for the Sun. We show that to make an interface dynamo work with the constraints of interior structure and skin depth, a meridional circulation is essential.

(ii) Any large-scale magnetic fields present in solar/stellar radiative interiors have so far been thought to be primordial or residuals from extinct dynamos. We [3] show that a regular cyclic dynamo can also be the origin of strong magnetic fields in the solar radiative tachocline and interior below. We show that, for a low enough core-diffusivity ($\leq 10^7\,\mathrm{cm}^2\,\mathrm{s}^{-1}$), there exists an oscillatory magnetic field as well as a steady (nonreversing) field of amplitude $\sim 1\,\mathrm{kG} - 3 \times 10^3$ kG or more. The Lorentz force feedback may limit oscillatory dynamo fields to $\sim$ 30 kG, for which the mean non-reversing toroidal fields is still $\sim$300 kG, for the lowest core diffusivity value. The presence of strong oscillatory and steady toroidal fields in the radiative tachocline implies that there cannot be a slow tachocline; the dynamics should always be fast there, dominated by MHD.

(iii) We [4, 5] construct a dynamo-based tool for predictions of mean solar cycle features by replacing the theoretical Babcock-Leighton type poloidal source with the observed surface magnetic source from decay of active regions. We run the model by assimilating the surface magnetic data since cycle 12, and show that the model can correctly simulate the relative peaks of cycles 16 through 23. The simulations use the first 4 cycles to load the meridional circulation conveyor belt to create the Sun's memory about its past magnetic fields. Extending the simulation into the future we predict that cycle 24 will be 30-50% stronger than current cycle 23. We show that the key to success of our prediction model lies in the formation of a 'seed' for producing cycle n from the combination of latitudinal fields at high latitudes from past three cycles, n-1, n-2 and n-3, instead of just previous cycle's polar fields, as used in so-called "precursor" prediction methods.

Finally we close by mentioning a few open problems for future research in this field: (i) simulating features in north and south hemispheres separately to look for additional forecast skill, as well as the influence of magnetic links between the two hemispheres, (ii) extenion of simulations of relative cycle peaks back to the earliest usable records, starting with cycle 1 around 1750, (iii) additional tuning of the model to improve the skill at predicting two sunspot cycles ahead. Two particularly important generalizations that need to be done are: to include departures from axisymmetry, since many solar cycle features are longitude-dependent, and to include **jxB** force type feedbacks on the differential rotation and meridional circulation.

References

[1] H. W. Babcock 1961. *The Topology of the Sun's Magnetic Field and the 22-YEAR Cycle*, The Astrophysical Journal **133**, 572 – 589.

[2] M. Dikpati, P. A. Gilman and K. B. MacGregor 2005. *Constraints on the Applicability of an Interface Dynamo to the Sun*, The Astrophysical Journal **631**, 647 – 652.

[3] M. Dikpati, P. A. Gilman and K. B. MacGregor 2006. *Penetration of Dynamo-generated Magnetic Fields into the Sun's Radiative Interior*, The Astrophysical Journal **638**, 564 – 575.

[4] M. Dikpati, G. de Toma and P. A. Gilman 2006. *Predicting the strength of solar cycle 24 using a flux-transport dynamo-based tool*, Geophysical research Letters, **33**, L05102 – L05105.

[5] M. Dikpati and P. A. Gilman 2006. *Simulating and predicting solar cycles using a flux-transport dynamo*, The Astrophysical Journal, **in press**.